Lawrence Berkeley National Laboratory

Vector Boson Scattering measurements using the ATLAS detector at the LHC

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Outline

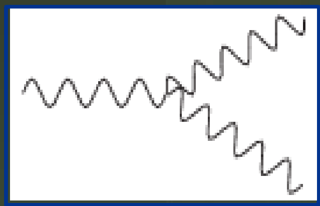
- **Why studying vector boson scattering (VBS) at the LHC?**
- **Experimental challenge**
- **First evidence of $W^{\pm}W^{\pm}jj$**

ATLAS-CONF-2014-013
27 March 2014

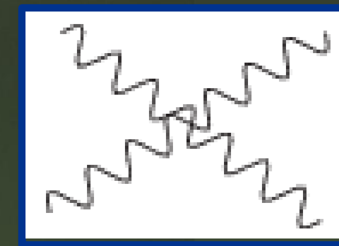
NEW

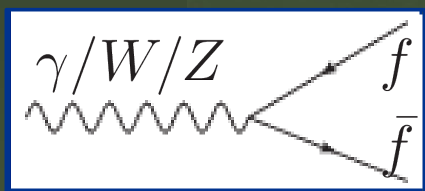
- **Future prospects**
- **Conclusions**

Electroweak sector of the Standard Model

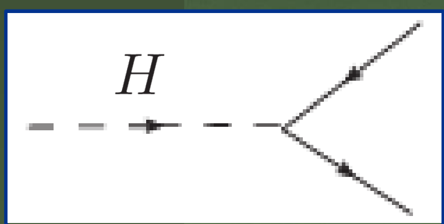


$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

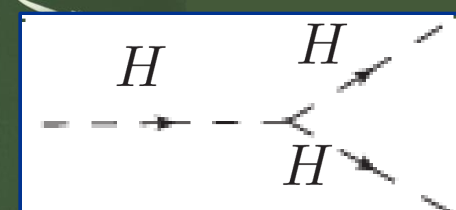


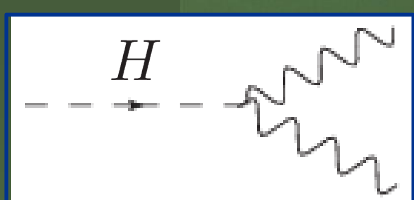


$$+ i\bar{\psi}\not{D}\psi + h.c.$$



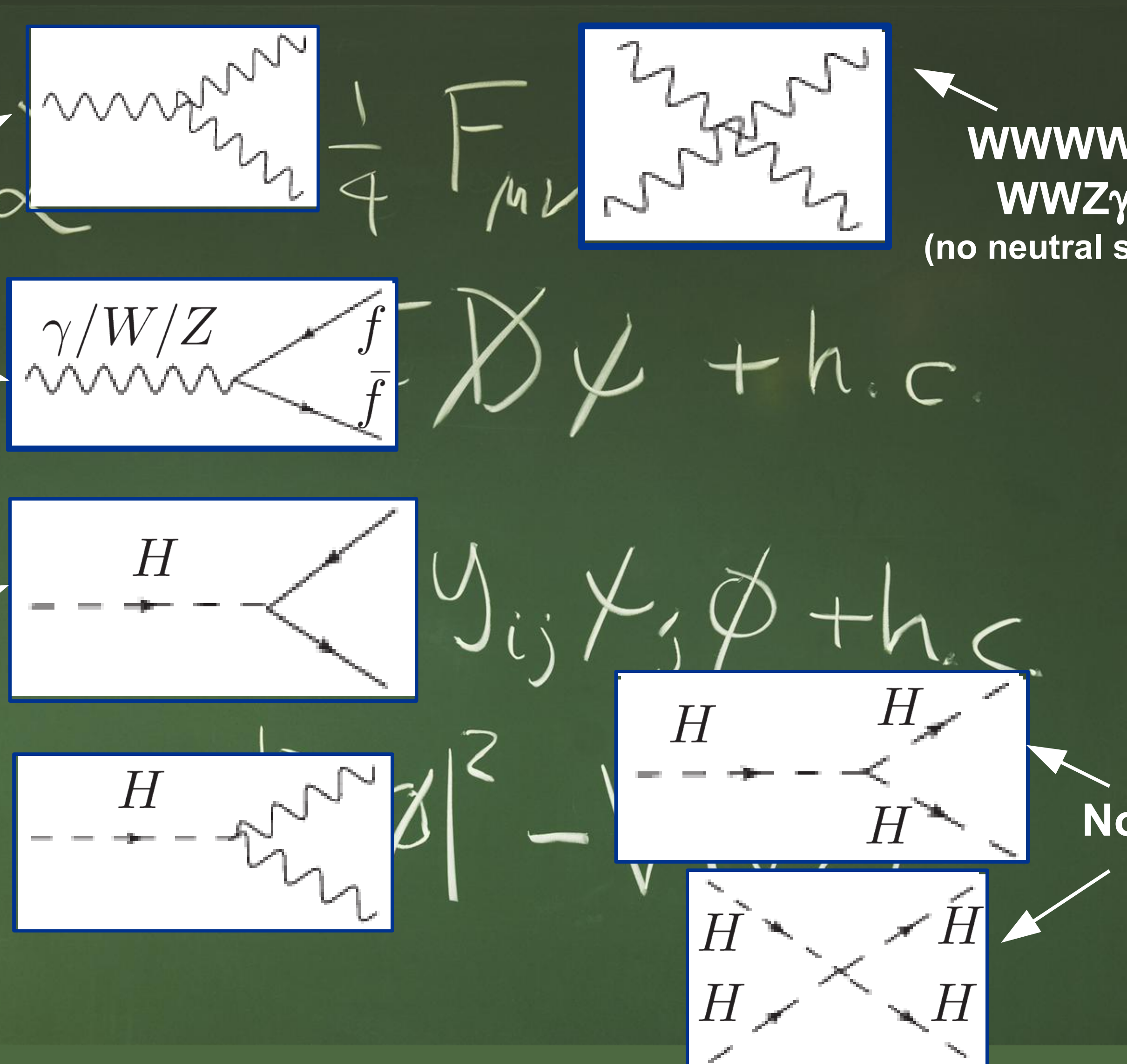
$$+ \psi_i y_{ij} \psi_j \phi + h.c.$$





$$+ |D_\mu \phi|^2 - V(\phi)$$

Electroweak sector of the Standard Model



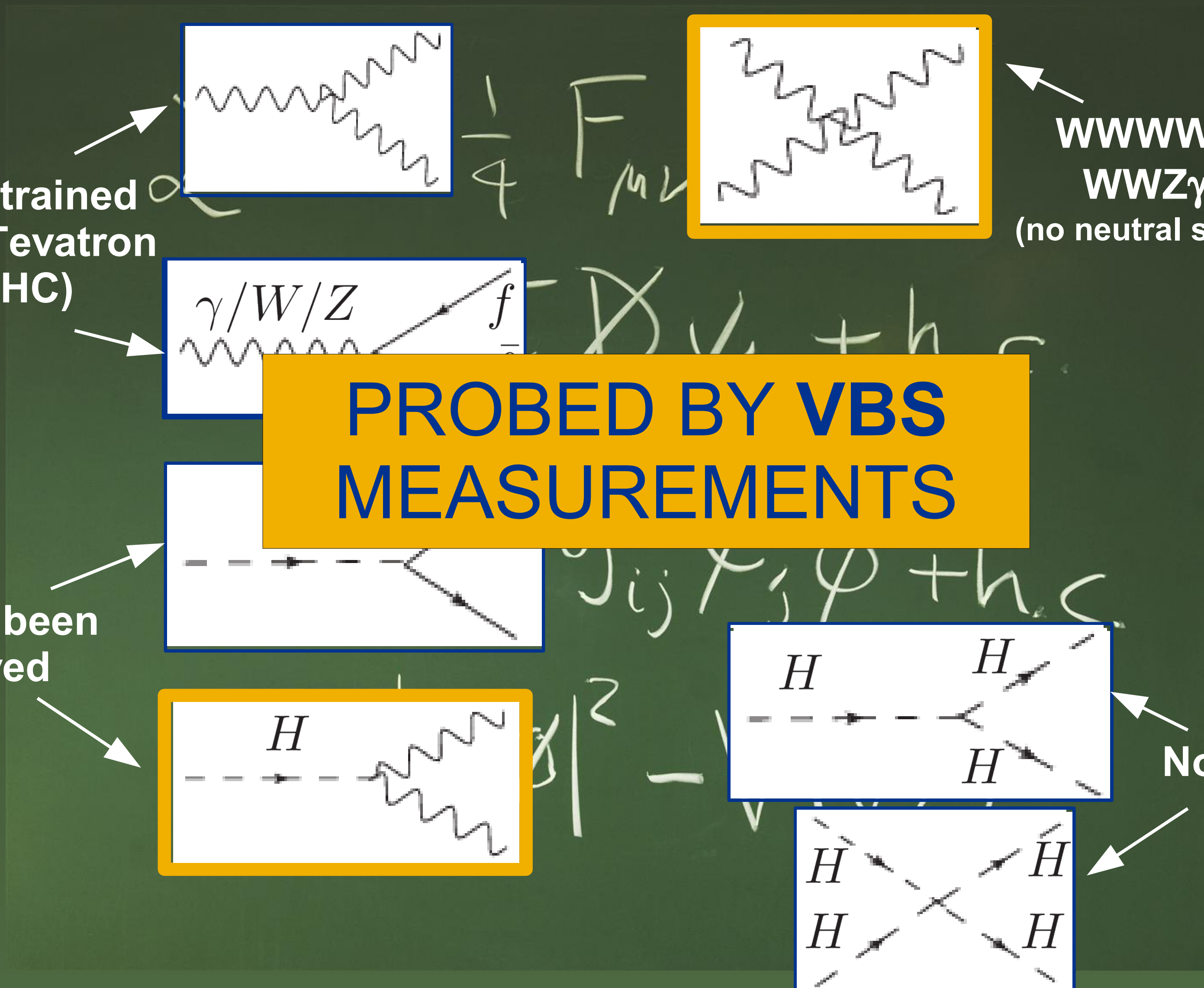
Well constrained (e.g LEP,Tevatron and LHC)

WWWW, WWZZ, WWZγ, WWγγ
(no neutral self-couplings)

Recently been observed

Not observed yet!

Electroweak sector of the Standard Model



Well constrained (e.g LEP,Tevatron and LHC)

WWWW, WWZZ, WWZγ, WWγγ
(no neutral self-couplings)

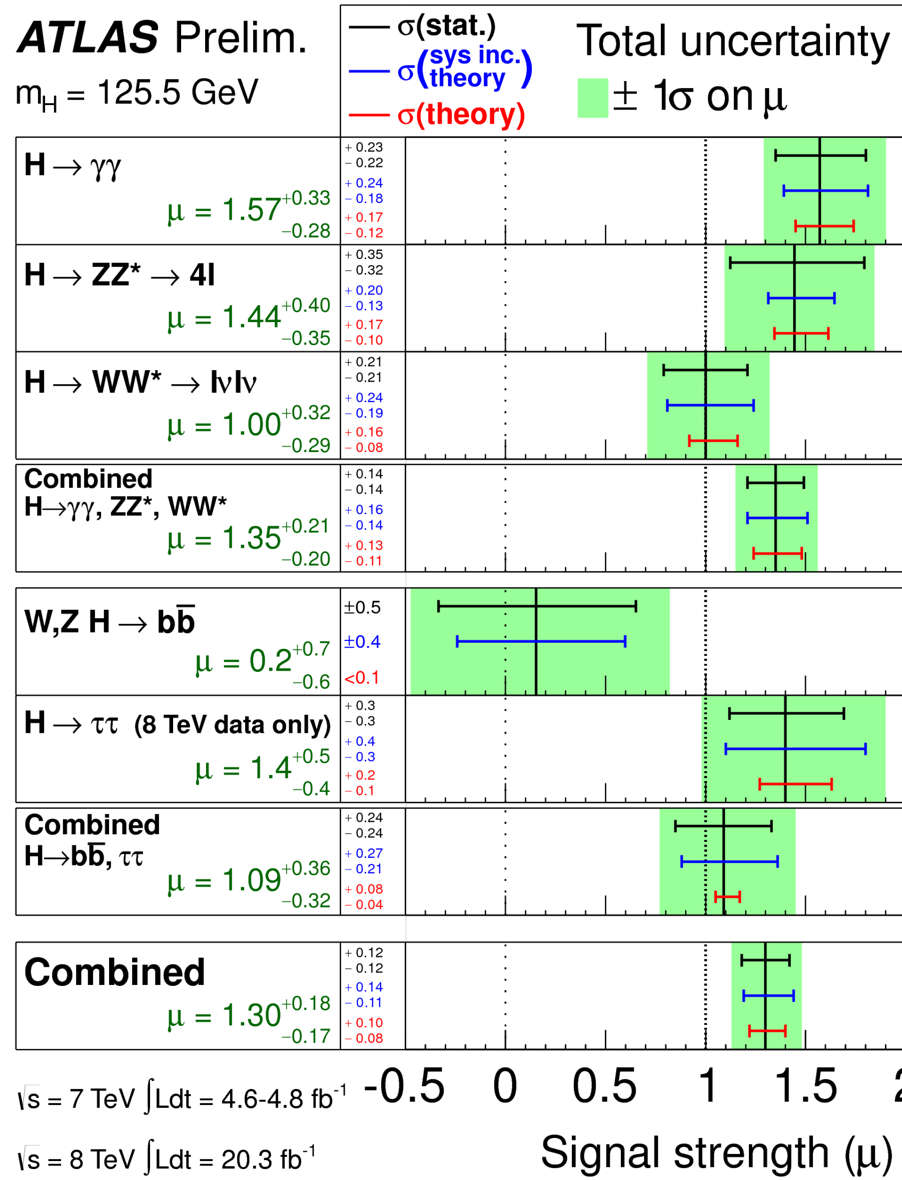
PROBED BY **VBS** MEASUREMENTS

Recently been observed

Not observed yet!

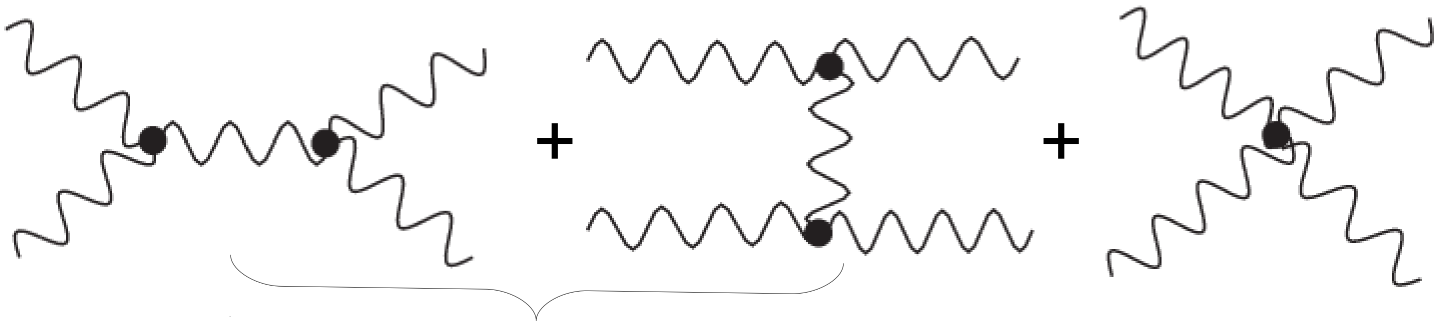
Higgs couplings measurements

- Couplings to vector bosons measured with 18-30% accuracy
  - expect ~10-20% in the next Runs of LHC
- Electro-weak symmetry breaking can also be explored in other complementary ways



VBS and the Higgs sector

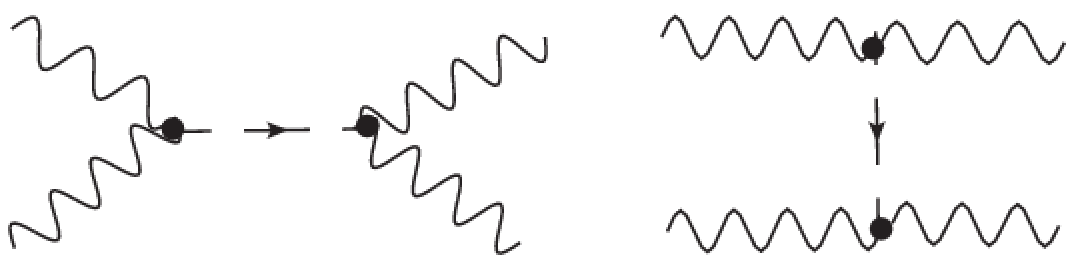
- $W_L W_L \to W_L W_L$ scattering violates unitarity (with no Higgs) ~ TeV



$$A(WW \to WW) \propto O(E^4) + O(E^4) \propto \underline{O(E^2)}$$

  - gauge self-coupling cancels E^4 dependency, E^2 left
  - SM Higgs boson cancels exactly the remaining E^2 dependency

+

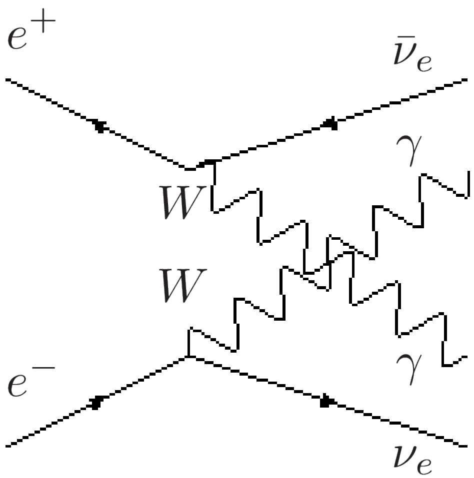


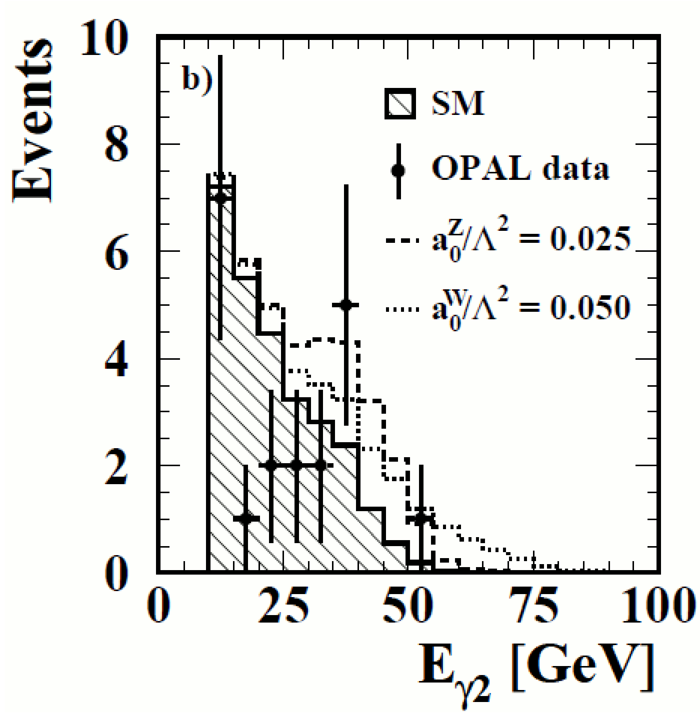
$$\propto \underline{O(1)}$$

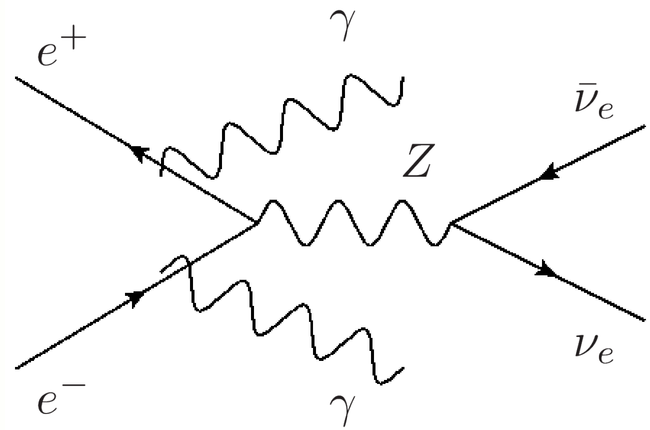
$$O(E^2)$$

VBS and quartic gauge couplings

- LEP: $e^+e^- \rightarrow \nu\nu\gamma$, $e^+e^- \rightarrow W^+W^-\gamma$; consistent with ISR/FSR contribution
  - Expected contribution from “WW-fusion” ~ 17% @ $s^{1/2}$=200 GeV





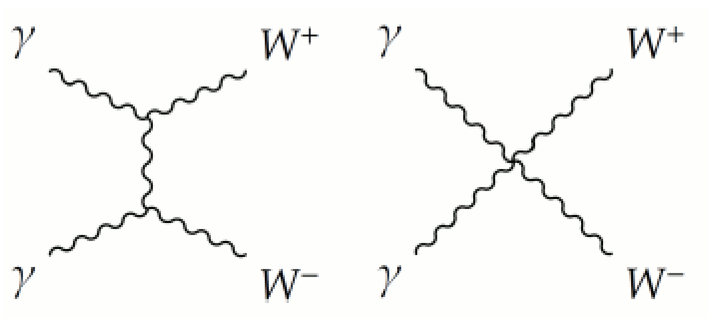


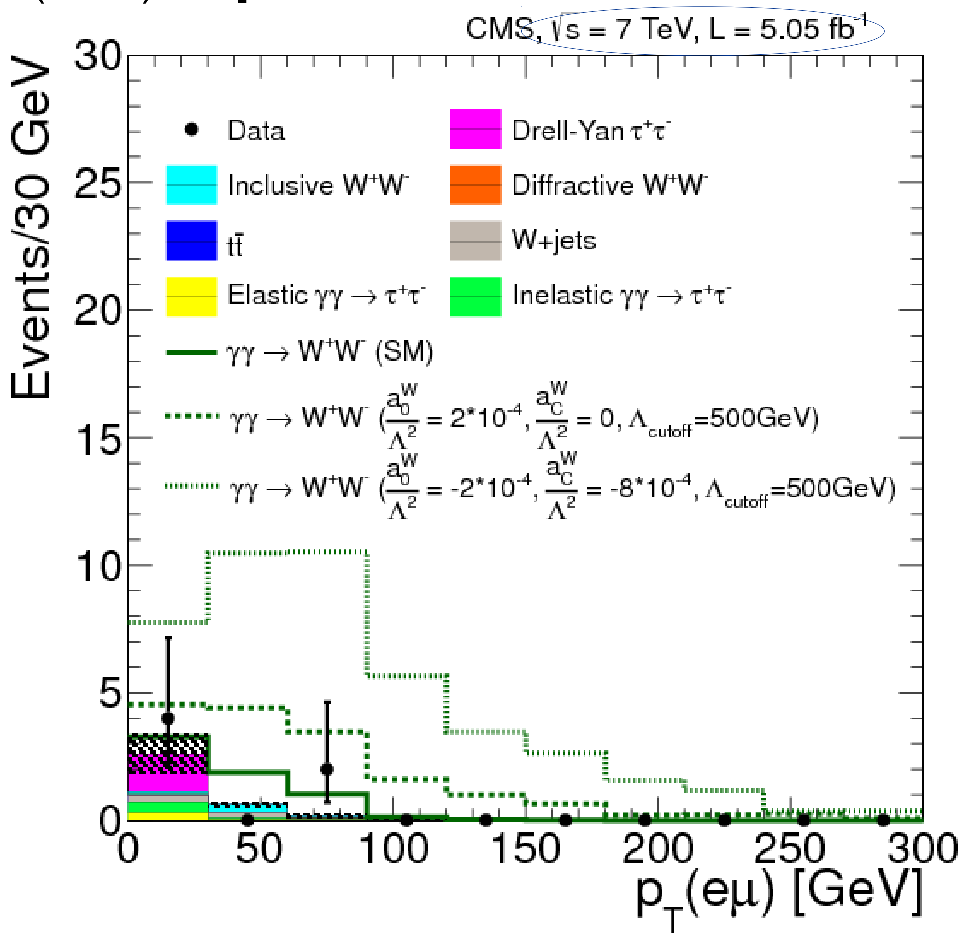
L3: http://arxiv.org/abs/hep-ex/0111029

OPAL: http://arxiv.org/abs/hep-ex/0402021

VBS and quartic gauge couplings

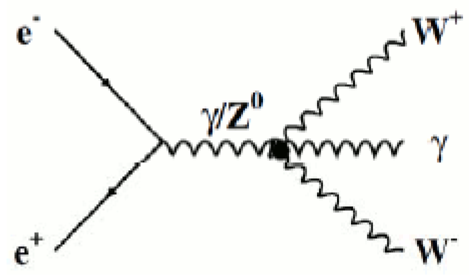
- LEP: $e^+e^- \rightarrow \nu\nu\gamma$, $e^+e^- \rightarrow W^+W^-\gamma$; consistent with ISR/FSR contribution
- CMS: $pp \rightarrow p^{(*)}\, W^+\, W^-\, p^{(*)}$ [JHEP 07 (2013) 216]
  - eμ decay channel,
  - No fragmentation tracks
  - Signal at ~1-2σ
  - Challenging to repeat at 8 TeV due to larger pile-up (but feasible?!)



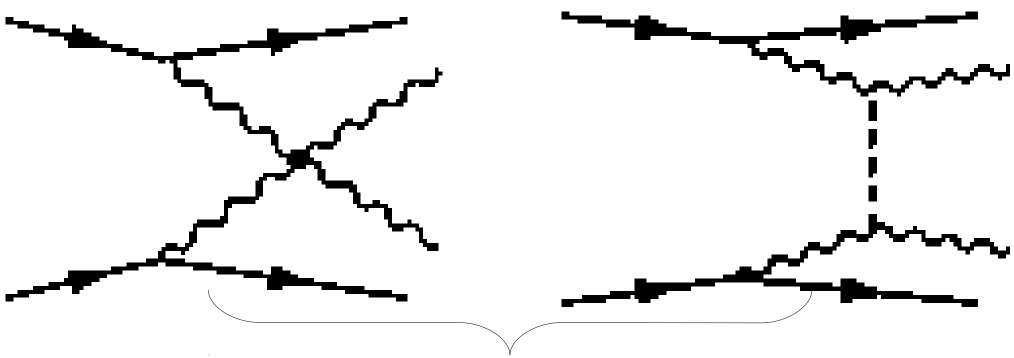


VBS and quartic gauge couplings

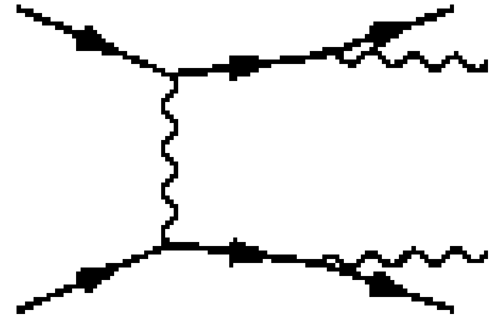
- LEP: $e^+e^- \rightarrow \nu\nu\gamma$, $e^+e^- \rightarrow W^+W^-\gamma$; consistent with ISR/FSR contribution
- CMS: $pp \rightarrow p^{(*)}\, W^+\, W^-\, p^{(*)}$ [JHEP 07 (2013) 216]
- Quartic gauge couplings also probed with triple vector boson production
  - LEP ($WW\gamma$), consistent with ISR/FSR
  - LHC (recent $WV\gamma$ result by CMS)
    - sensitivity about $3.4x\sigma_{SM}$



Overall, no direct evidence of a process involving four vector bosons vertex



VBS



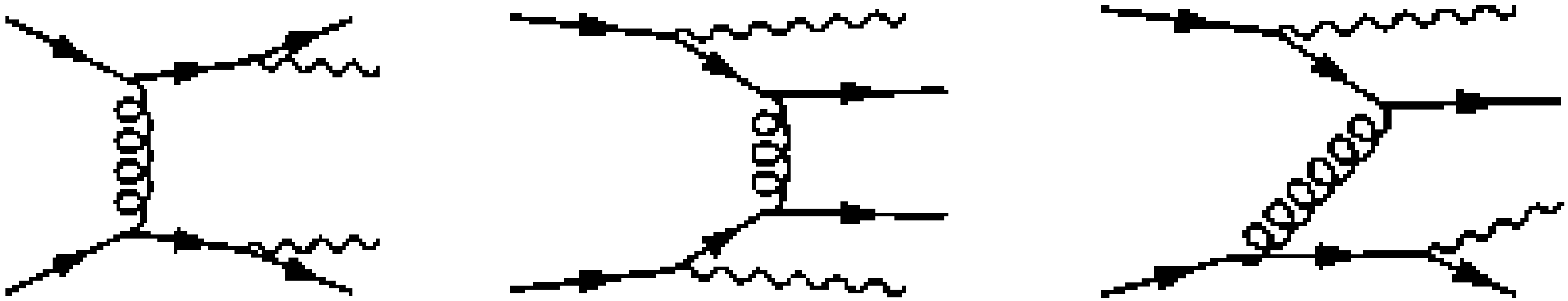
non-VBS

- **Electroweak production** (α_{EW}^4 at LO)
  - VBS not gauge invariant separately (e.g. Phys.Rev.D 74, 073010 (2006))

	σ (pb) all diagrams	σ (pb) WW diagrams	Ratio of WW/all diagrams
Unitary gauge	8.50×10^{-3}	6.5	765
Feynman gauge	8.50×10^{-3}	0.221	26
Axial gauge	8.50×10^{-3}	2.0×10^{-2}	2.3

  - Only makes sense to study the whole electro-weak production!

VBS at the LHC: VVjj (V=W,Z)



- Same final state: **Strong production** ($\alpha_s^2\alpha_{EW}^2$ at LO)

Final state	Process	VVjj-ewk	VVjj-strong	Ratio ewk:strong
$\ell^\pm\nu\ell'^\pm\nu'$jj	$W^\pm W^\pm$	19.5 fb	18.8 fb	1:1
$\ell^\pm\nu\ell'^\mp\nu'$jj	$W^\pm W^\mp + ZZ$	93.7 fb	3192 fb	1:30
$\ell^\pm\ell^\mp\ell'^\pm\nu'$jj	$W^\pm Z$	30.2 fb	687 fb	1:20
$\ell^\pm\ell^\mp\ell'^\pm\ell'^\mp$	ZZ	1.5 fb	100 fb	1:70

SHERPA, LO at $\sqrt{s} = 8$ TeV. $p_T(\ell) > 5$ GeV, $p_T(j) > 15$ GeV, $m(\ell\ell) > 4$ GeV.

- **W± W± j j** : the golden channel for favorable sig/bkg contribution
  - only an handful of events expected after selections!

Outline

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- **Experimental challenge**
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- Future prospects
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the Large Hadron Collider

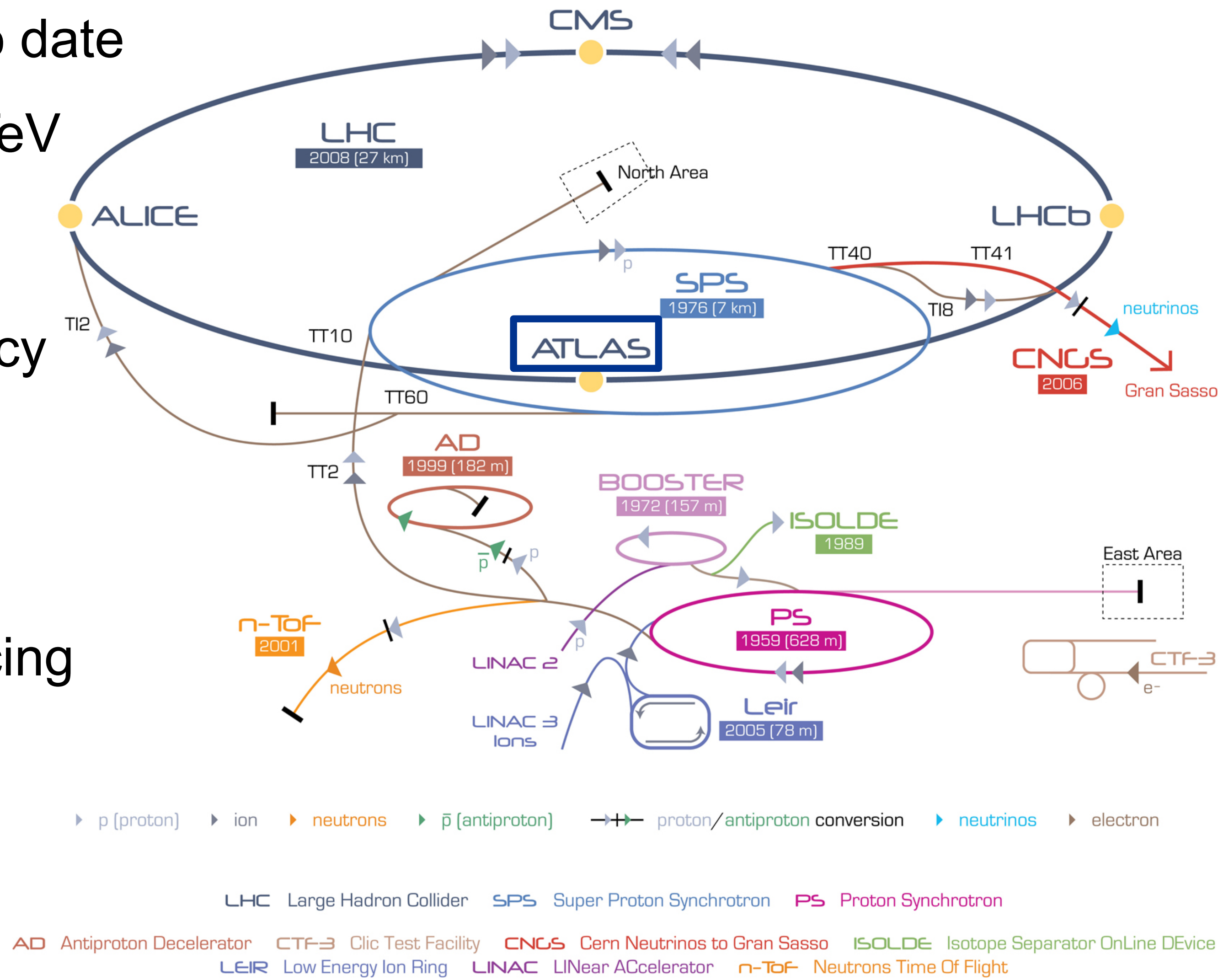
- Last stage of accelerator complex at CERN (protons, Pb ions)
- Performance up to date

  - protons up to 4 TeV per beam

  - 11245.5 Hz revolution frequency

  - up to 1368 colliding bunches (11 “trains”)

  - 50ns bunch spacing

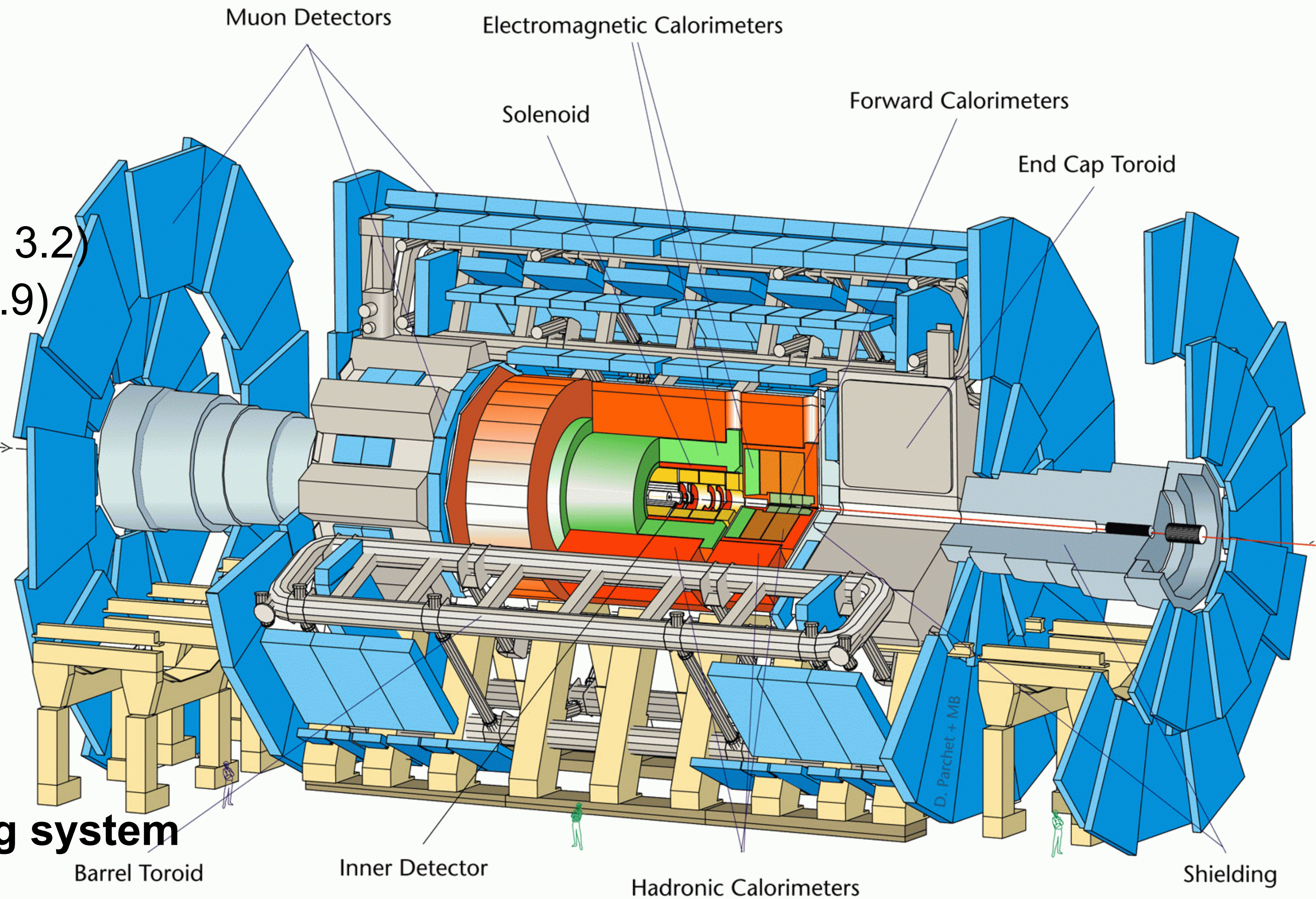


the ATLAS detector

Muon system ($|\eta| < 2.7$)
Strong bending power
(air-core toroid)
Trigger chambers

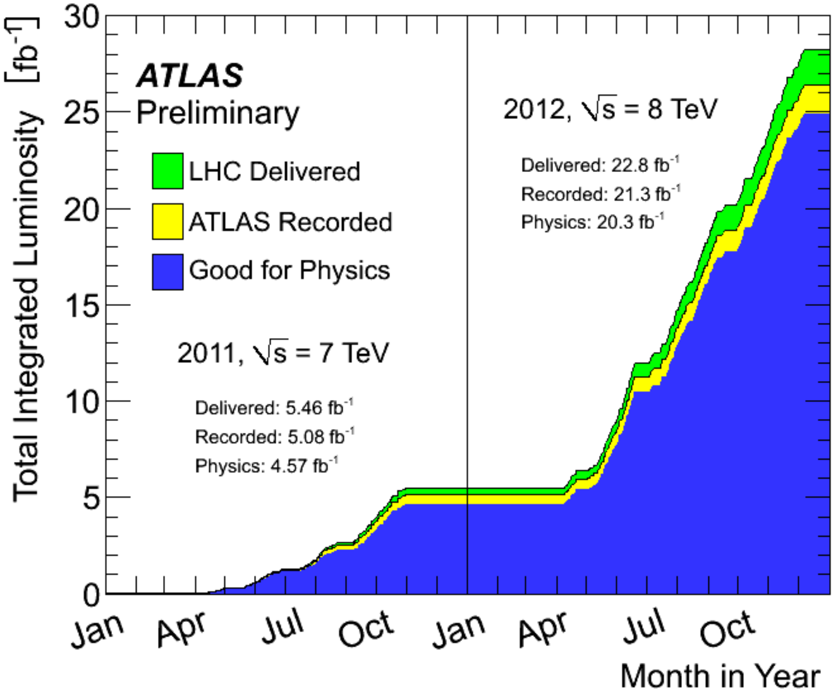
Calorimeters
Central,EndCap ($|\eta| < 3.2$)
Forward ($3.2 < |\eta| < 4.9$)

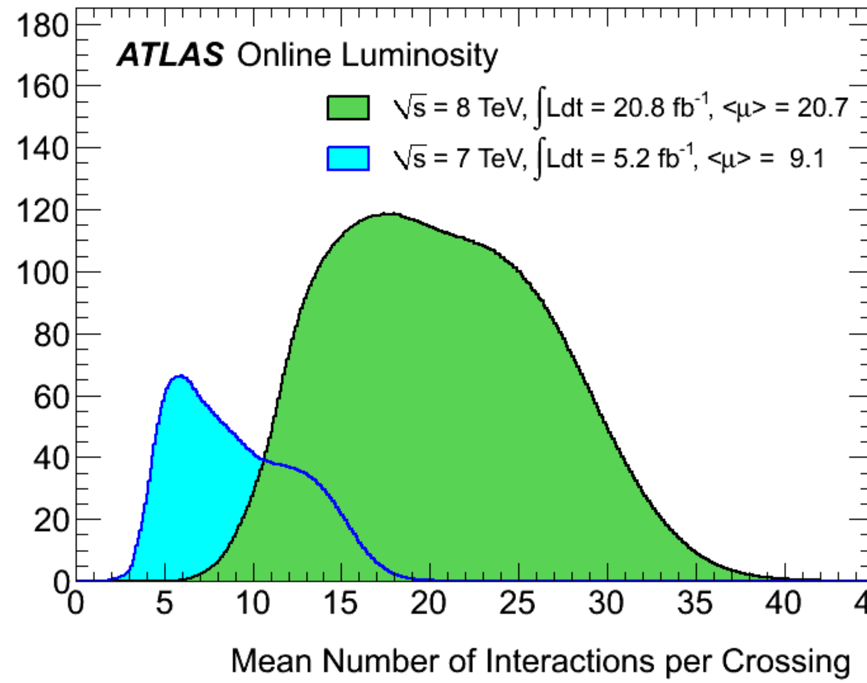
Tracking system
$|\eta| < 2.5$
Si Pixels, Strips,
Transition-Radiation
Tracker
2T magnetic field



Three-level **triggering system**
Output rate ~400 Hz
Single e,μ triggers un-prescaled with p_T >~ 24 GeV

Luminosity and pile-up





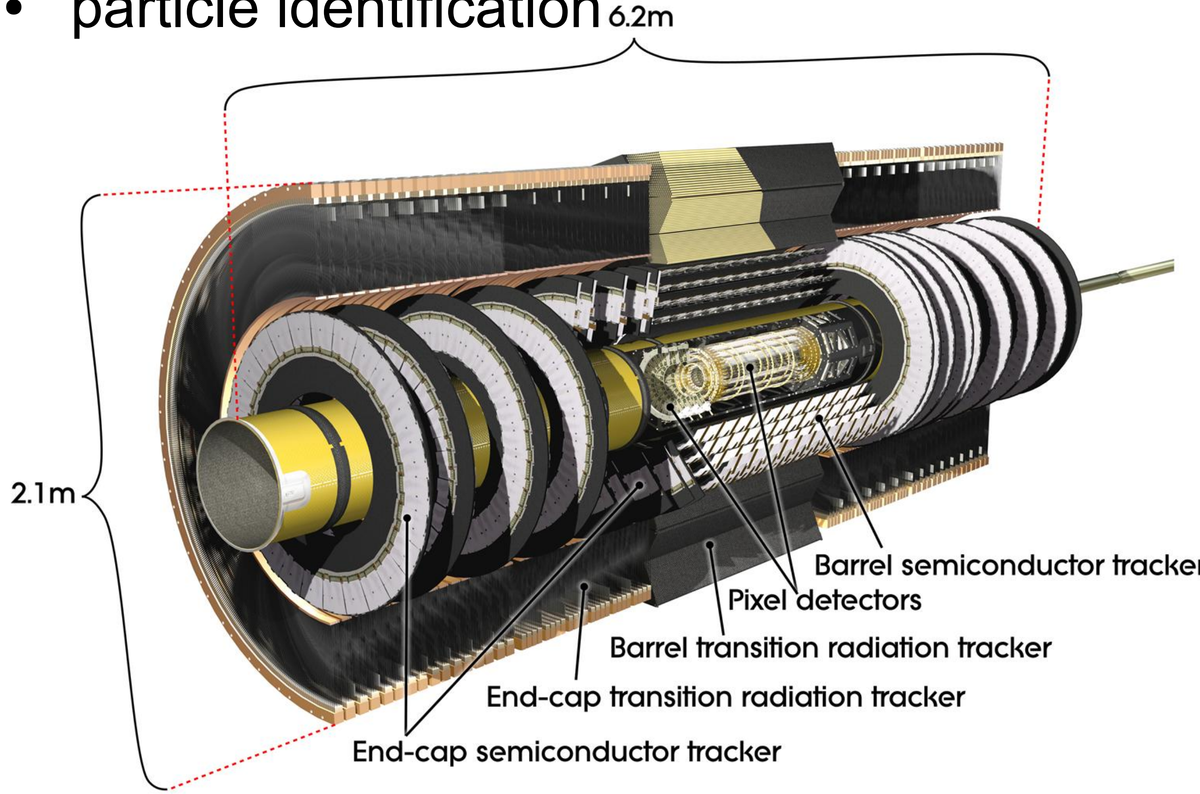
- Delivered integrated luminosity up to 28.3fb^{-1}
  - 22.8 fb^{-1} @ s$^{1/2}$ = 8 TeV

$$< \mu >= \frac{L \cdot \sigma_{\mathrm{inel.}}}{N_{\mathrm{bunch}} \cdot f_{\mathrm{LHC}}}$$

- Single sub-detectors > 99% efficient, ~90% of delivered for analysis
- Challenging conditions for experiments (L up to ~7.7·10^{33} cm^{-2}s^{-1})
  - <u>Mean number of p-p interactions per crossing up to ~40</u>

Inner Tracking Detector (ID)

- Charged particles trajectories, p_T > 400 MeV
- Vertex reconstruction
- b-tagging in jets
- particle identification



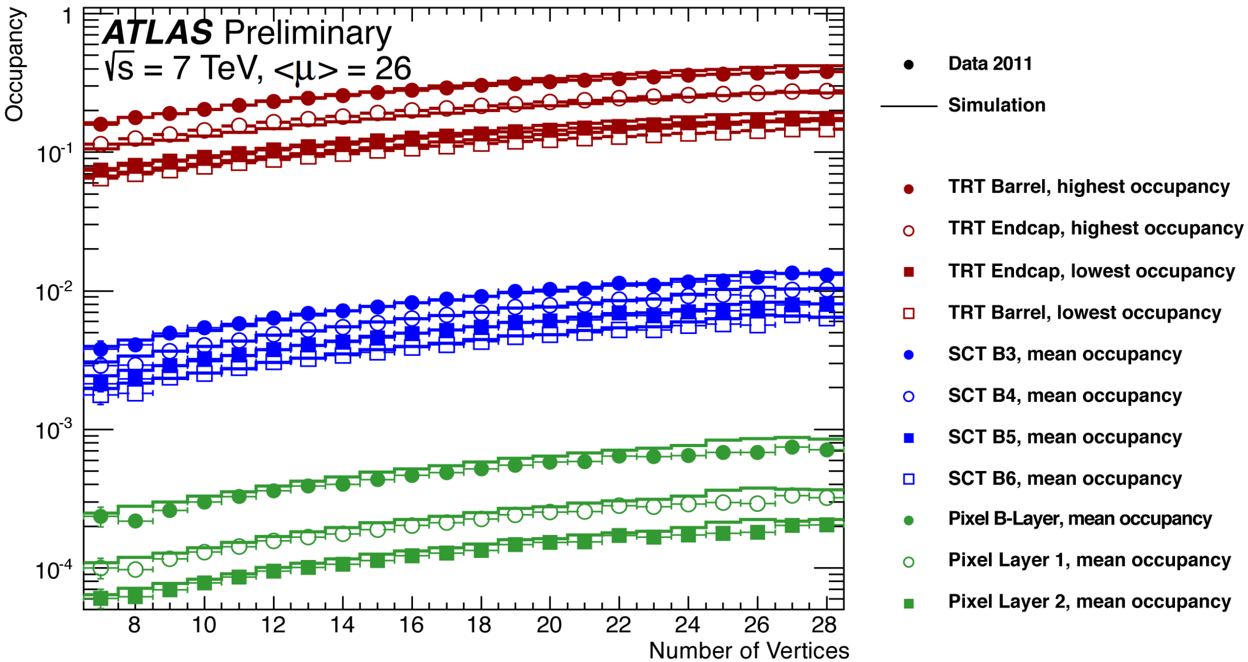
Pixel detector
80M silicon pixels,
50x400μm^2 (90%)
3 barrels and 2x3 end-caps
<hits/track> ~ 3

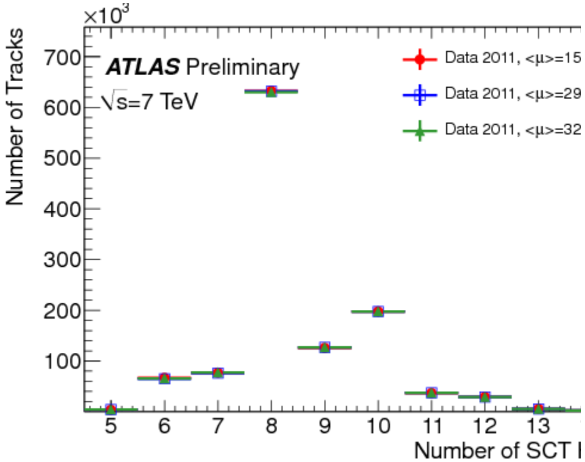
Semiconductor Tracker
6.3M silicon strips, 80μm pitch
4 barrels and 2x9 end-caps
<hits/track> ~ 8

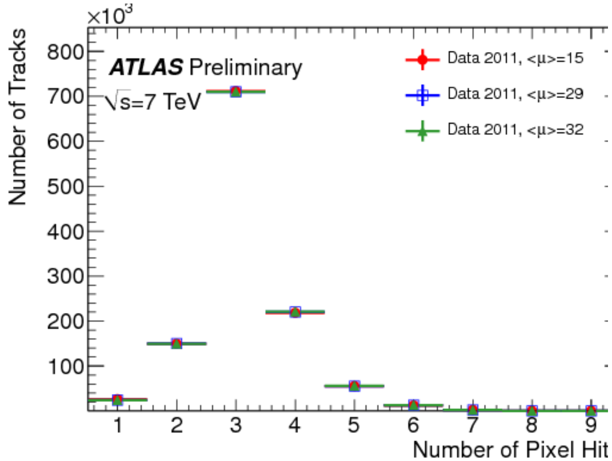
Transition radiation tracker
350K straws, 4mm. 73 barrel and 160 end-cap planes
<hits/track>~30

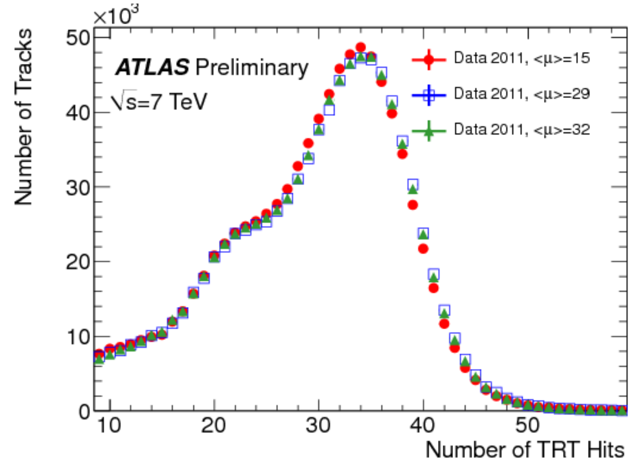
Pile-up as seen by ID sub-detectors

- Detector occupancy well modeled by simulation
- Available number of measurements per track stable against increased occupancy



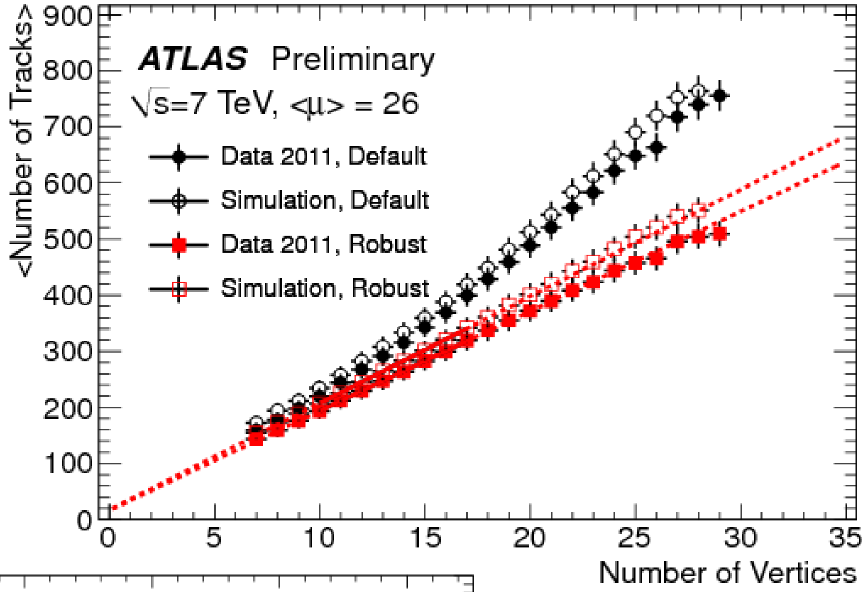


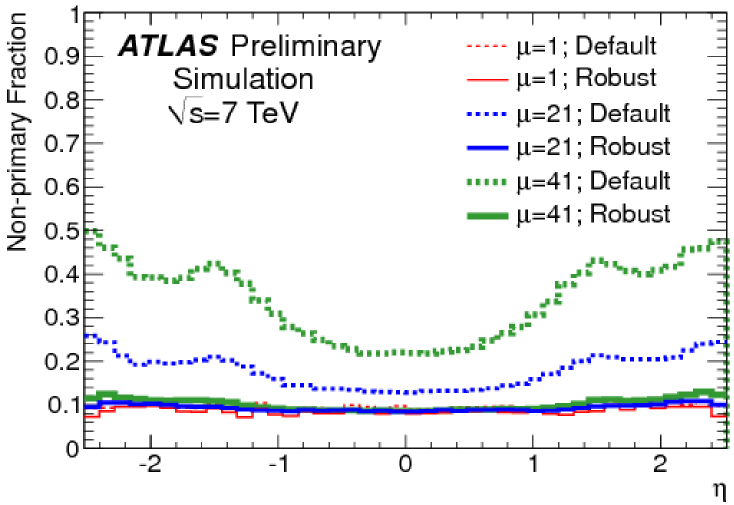


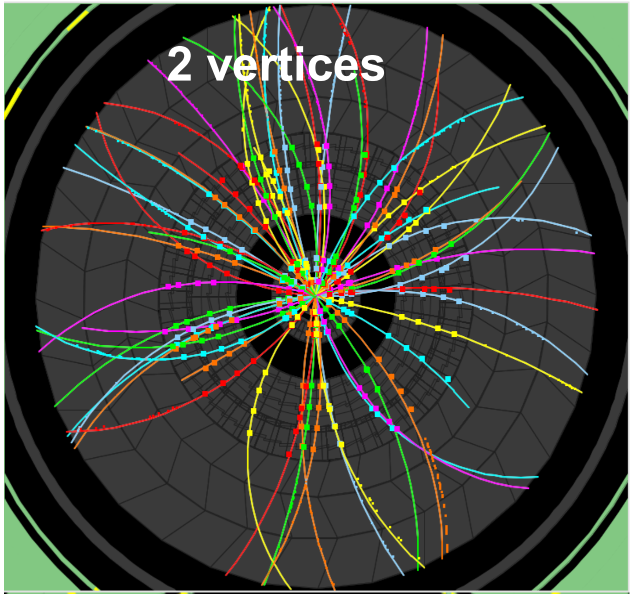


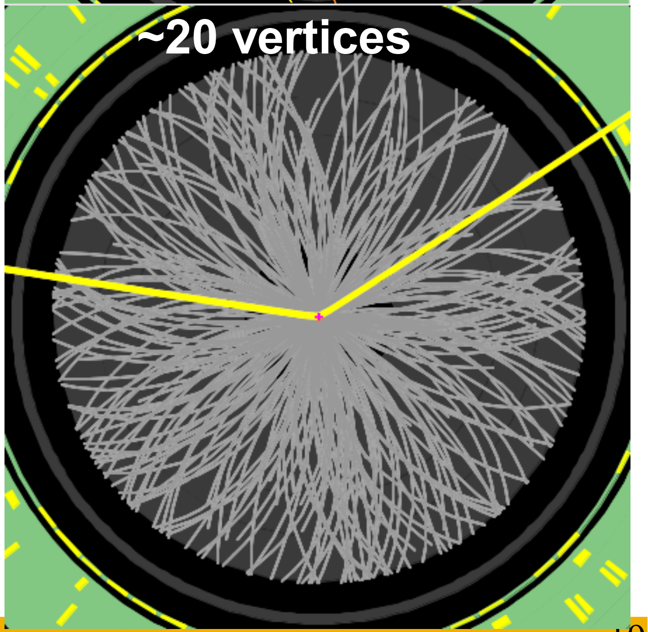
Mitigating pile-up effects

- Combinatorial fake tracks increase with pile-up



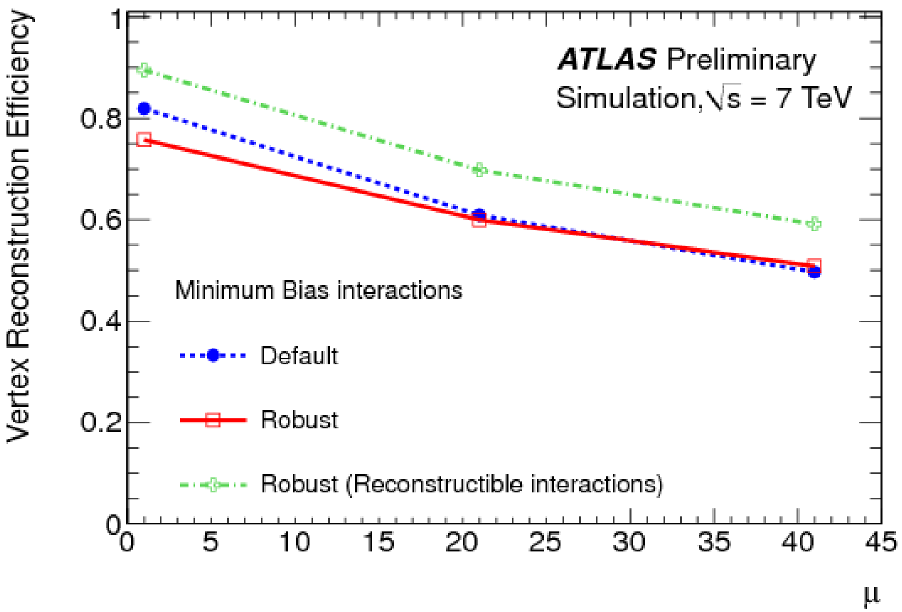


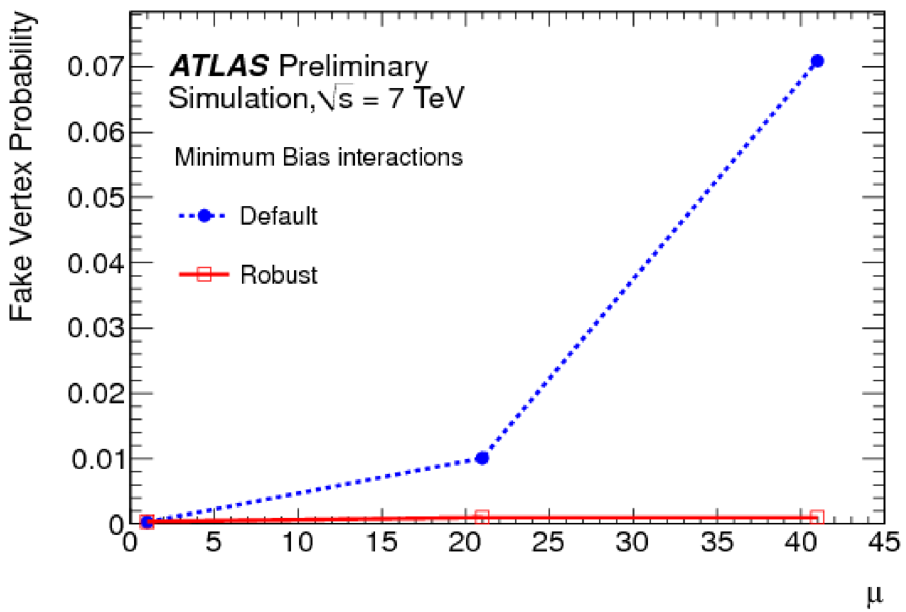




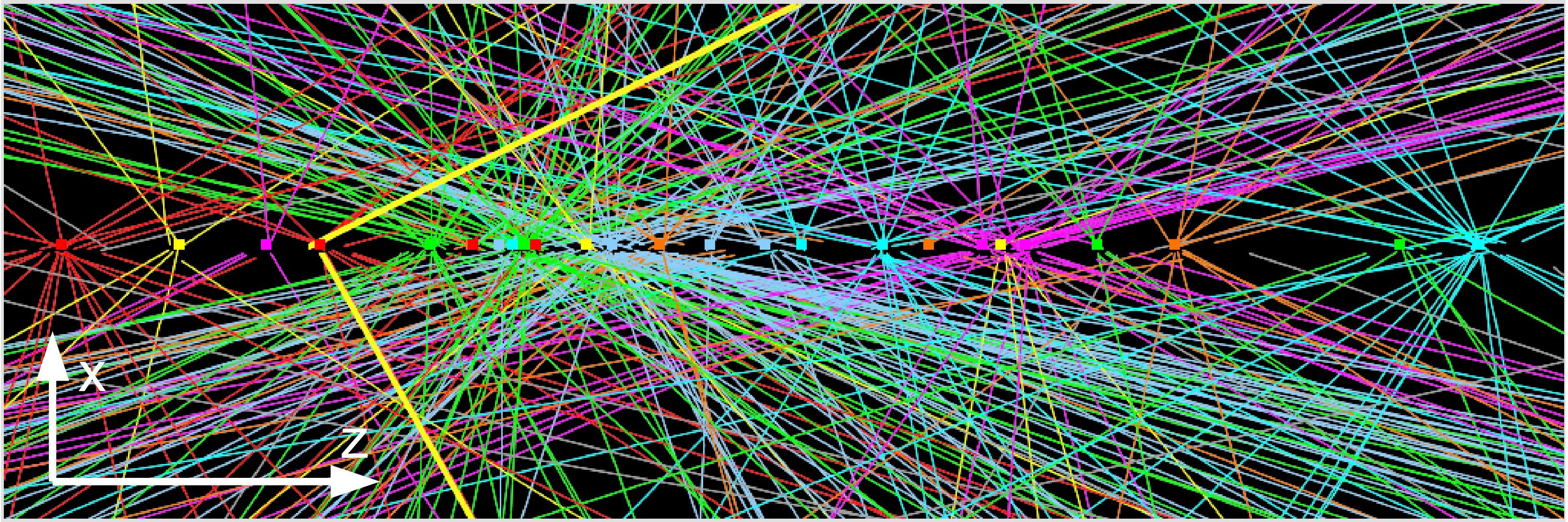
Primary vertex reconstruction

- Iterative algorithm optimized for precision of position measurement
- Quality requirement if input tracks re-optimized for 2012 data taking
  - Tighter track selection for vertex reconstruction reduces fakes with similar (or improved) efficiency at high pile-up



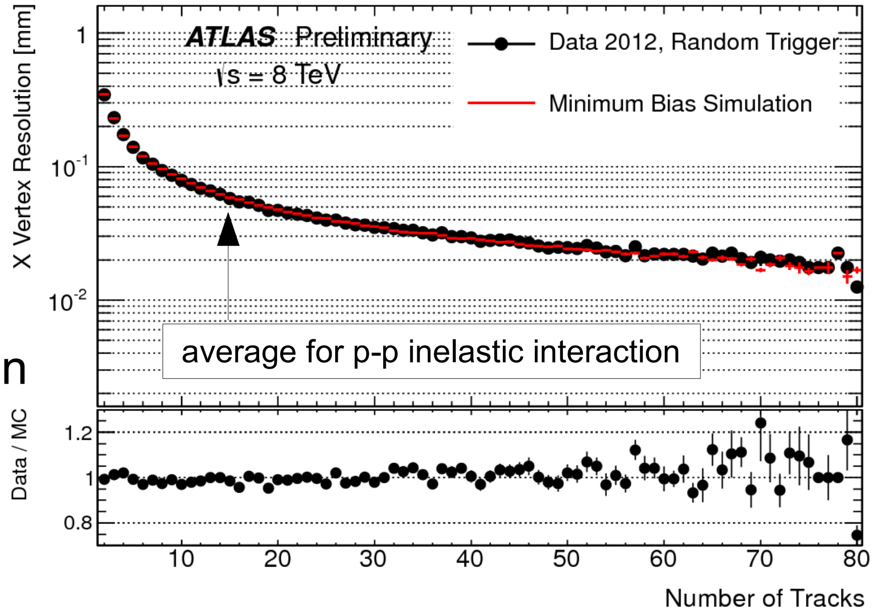


Distinguishing pile-up interactions

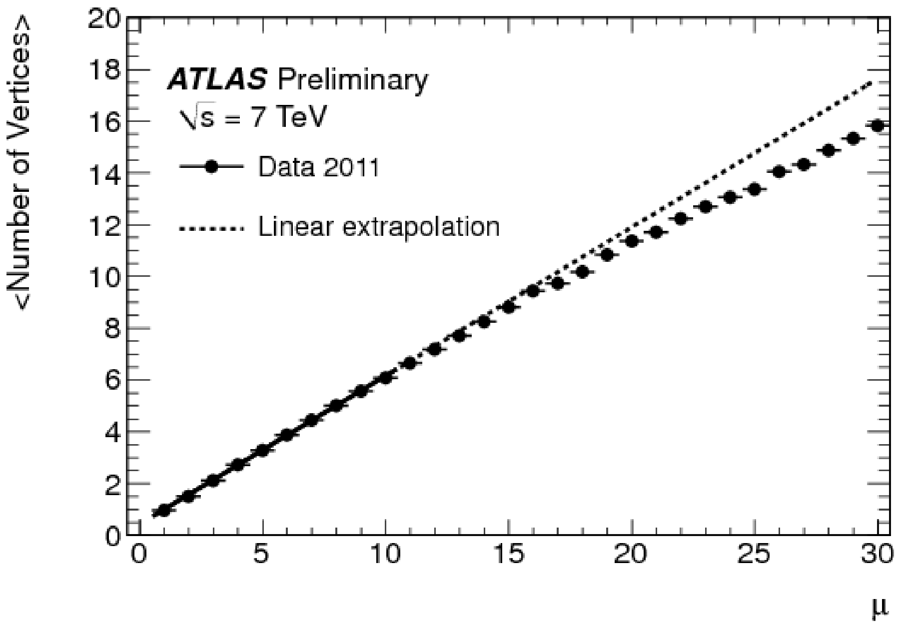


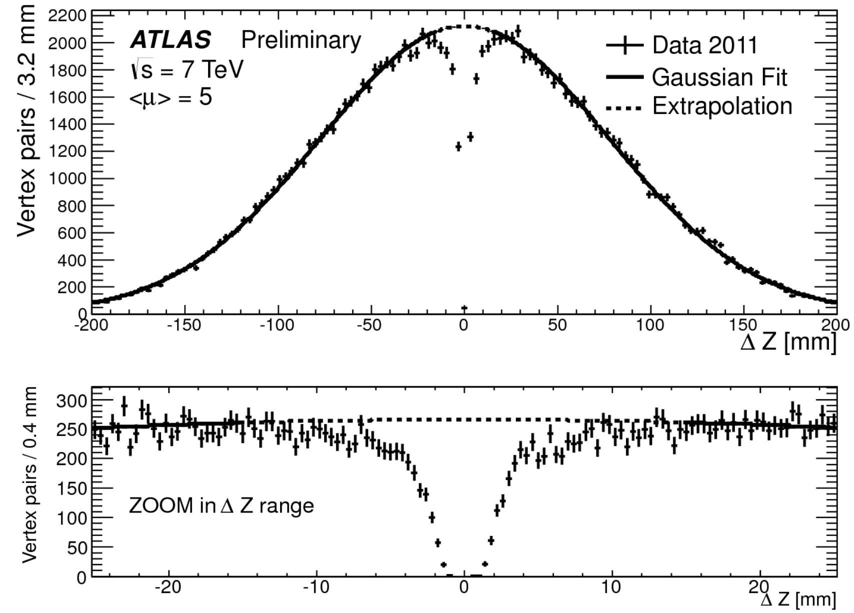
Interaction region (~Gaussian):
Transverse size (σ): 12-16 μm
Longitudinal size (σ): 45-50 mm
[average 2012 data]

Transverse size << average vertex resolution
Distinguish interactions only along z



Distinguishing nearby interactions

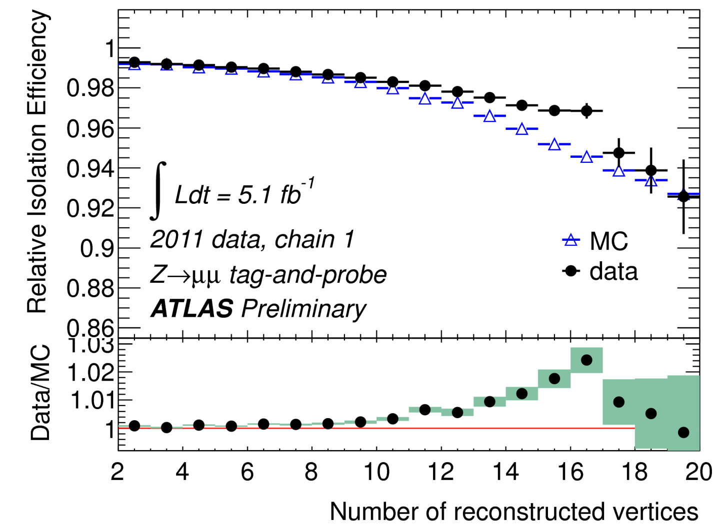




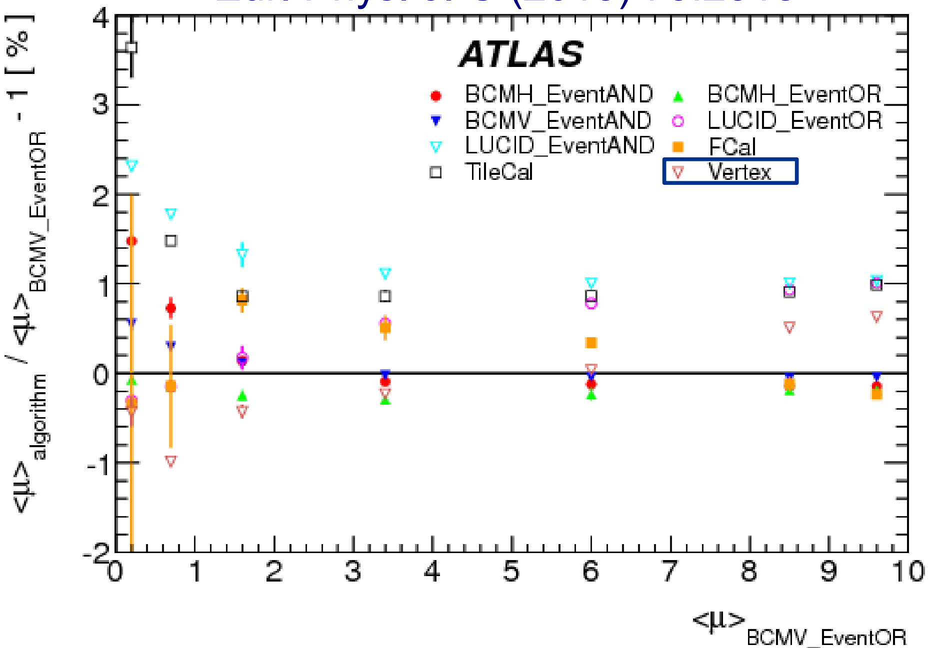
- Resolving nearby interaction needs to compromise between:
  - efficiency of reconstructing distinct vertices
  - probability of "splitting" a single interaction into two vertices (dangerous → kept << 1%)
- Loss of efficiency for nearby interactions manifest as non-linear behavior of <N_{VERTEX}> vs μ (μ determined by independent luminosity detectors)

Why is that important?

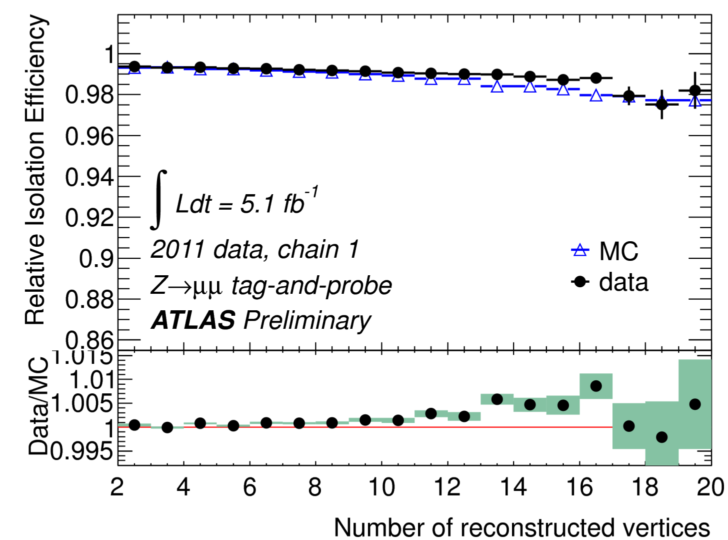
- Pile-up dependent corrections
  - e.g. subtraction of extra energy in leptons isolation cones
- luminosity monitor/measurement



Eur. Phys. J. C (2013) 73:2518

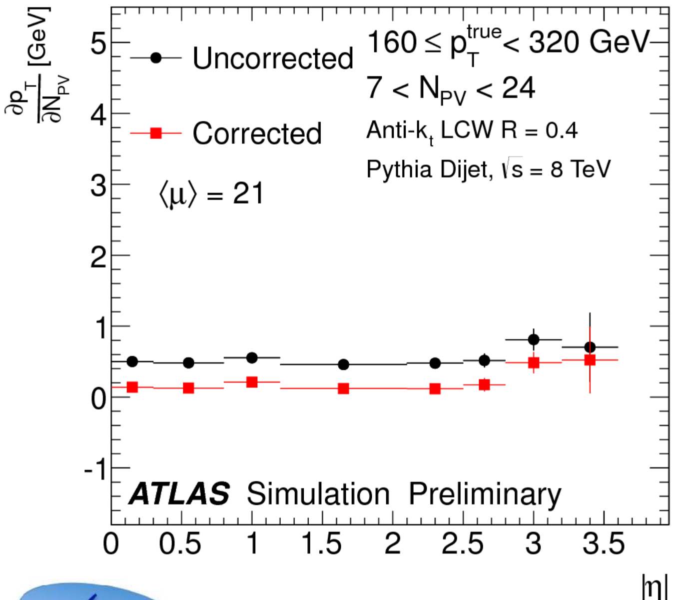


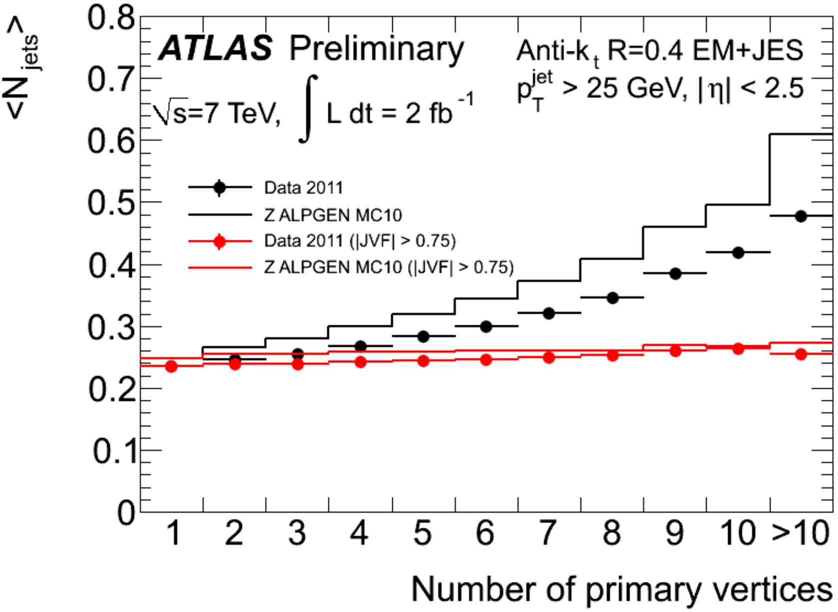
pile-up correction based on #vertices

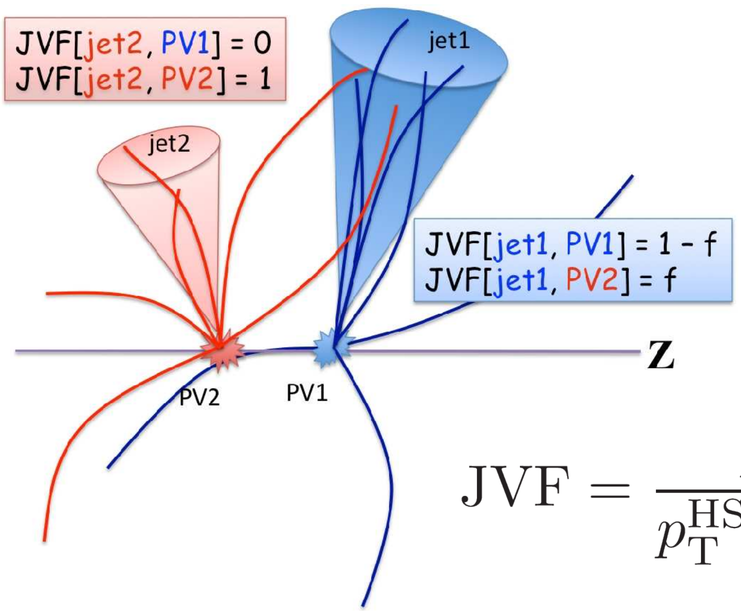


Pile-up in jets

- Contributes to energy of reconstructed jets (~0.5 GeV / vertex)
- Jets from pile-up interactions
  - Use reconstructed tracks to match jets to the hard-scattering primary vertex

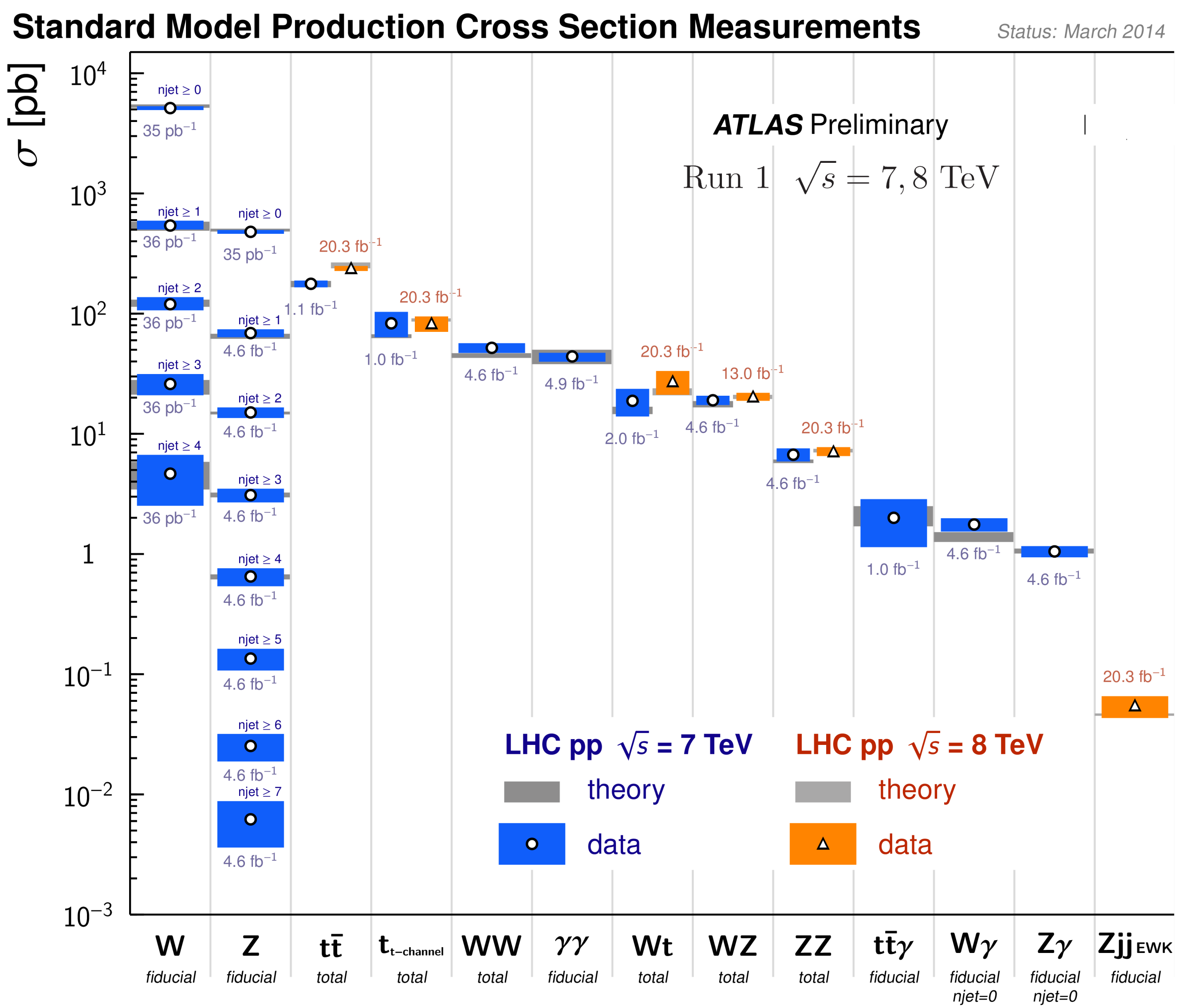




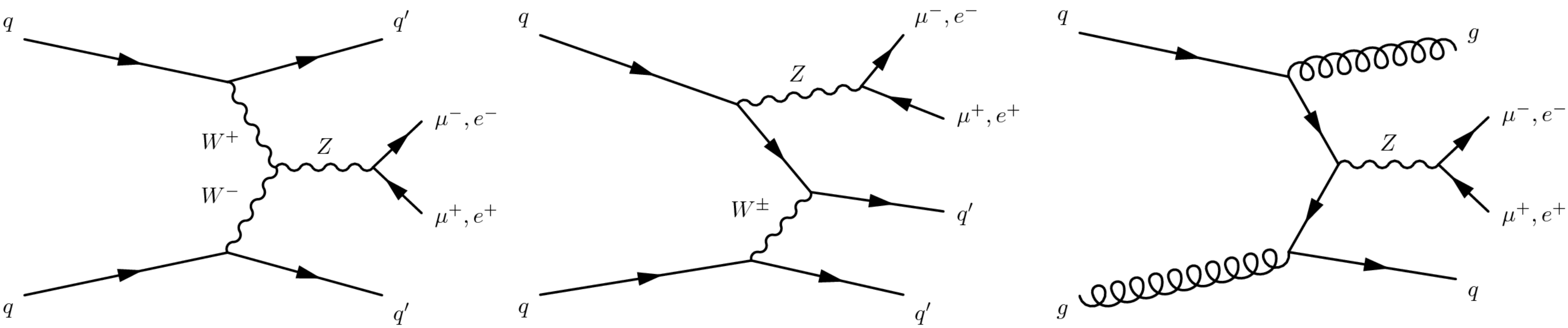


$$\mathrm{JVF} = \frac{p_T^{HS}}{p_T^{HS} + p_T^{PU}}$$

Measuring rare Standard Model processes



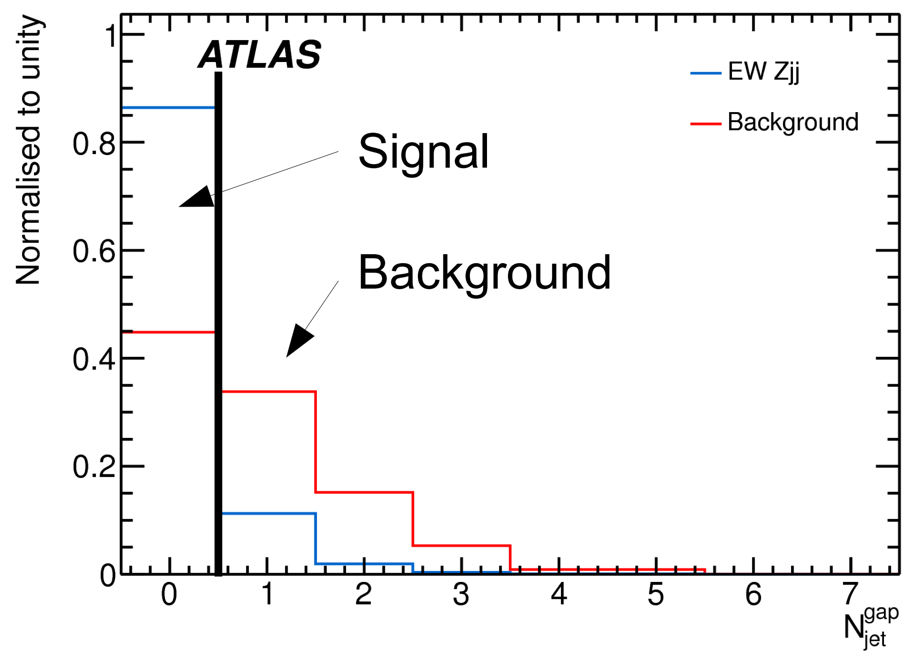
Electroweak Zjj production



Electro-weak production

Strong production

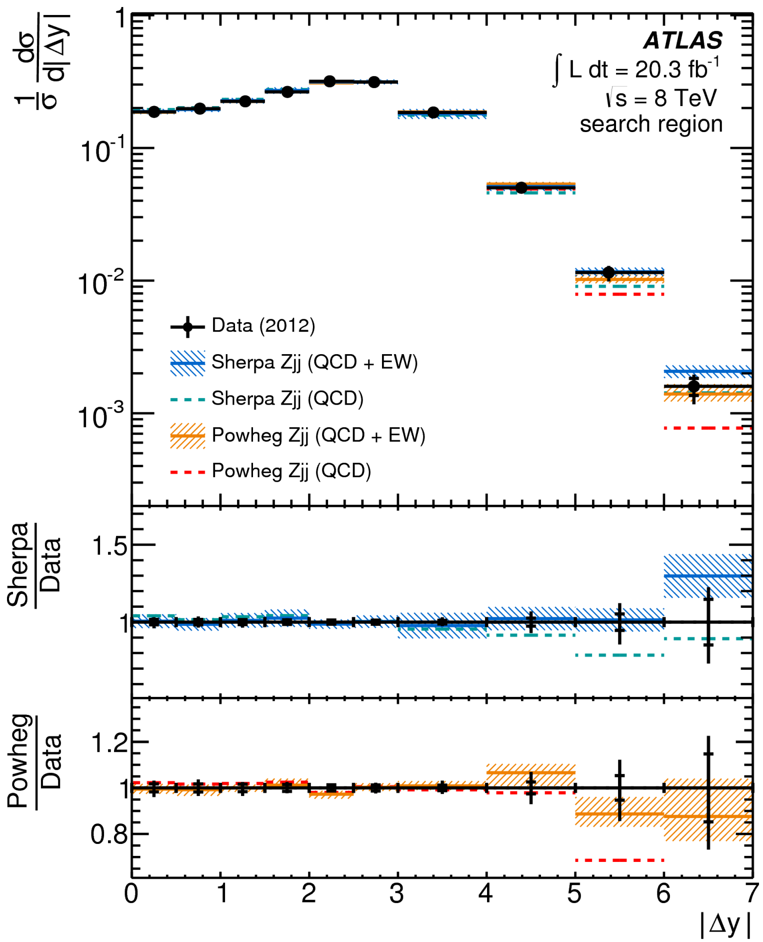
- Milestone towards VBS measurements
- Finale state: two opposite charge leptons (e, μ) and two jets
- Low jet activity for EWK
- Very small top, diboson residual background (2%)

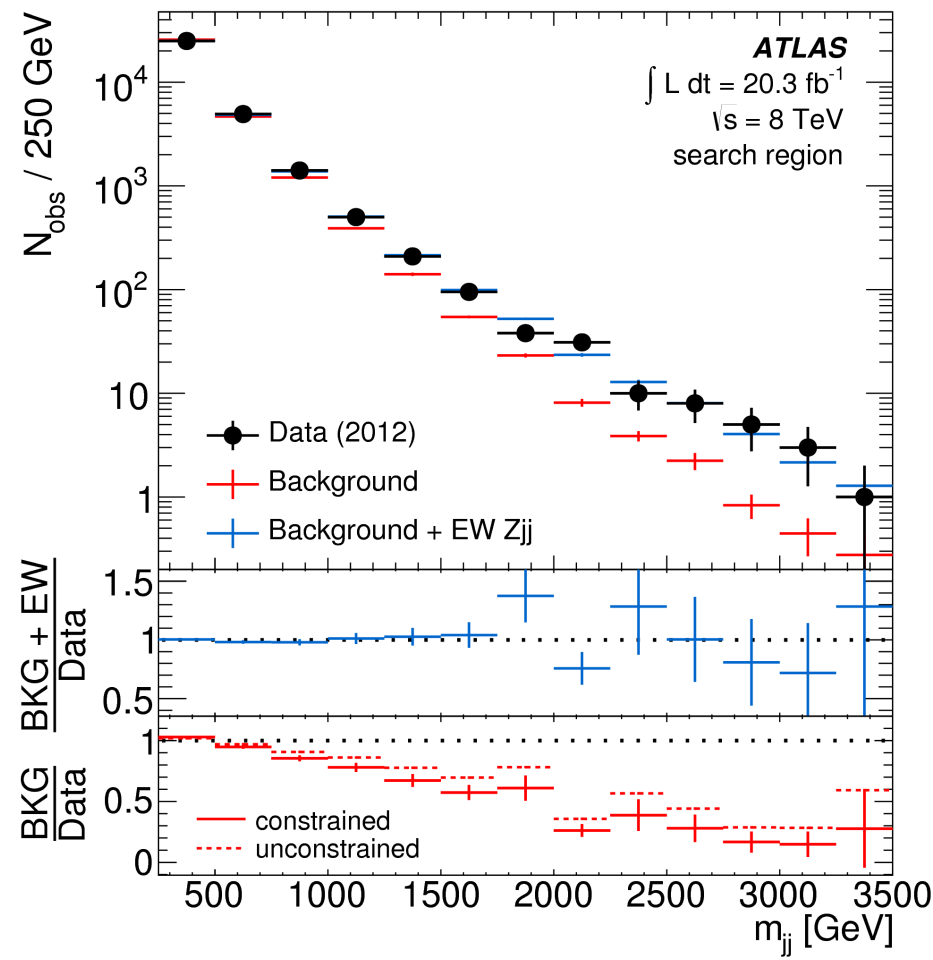


arXiv:1401.7610 (submitted to JHEP)

Results

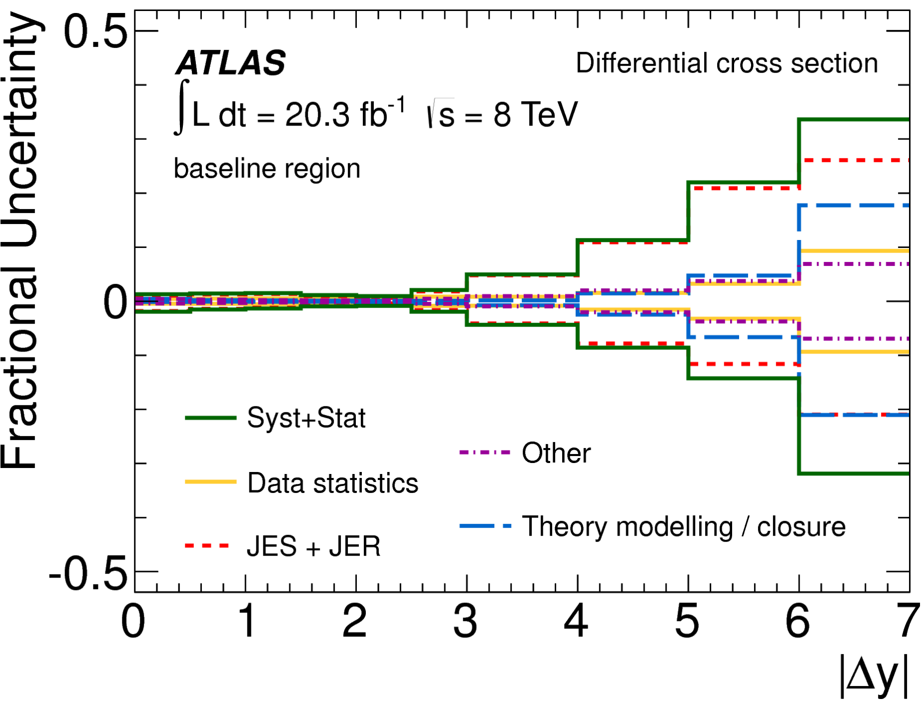
- Analyzed 20.3fb^{-1} of data @ s$^{1/2}$ = 8 TeV
- Observation of electroweak Zjj production at hadron colliders (background-only excluded at > 5σ)

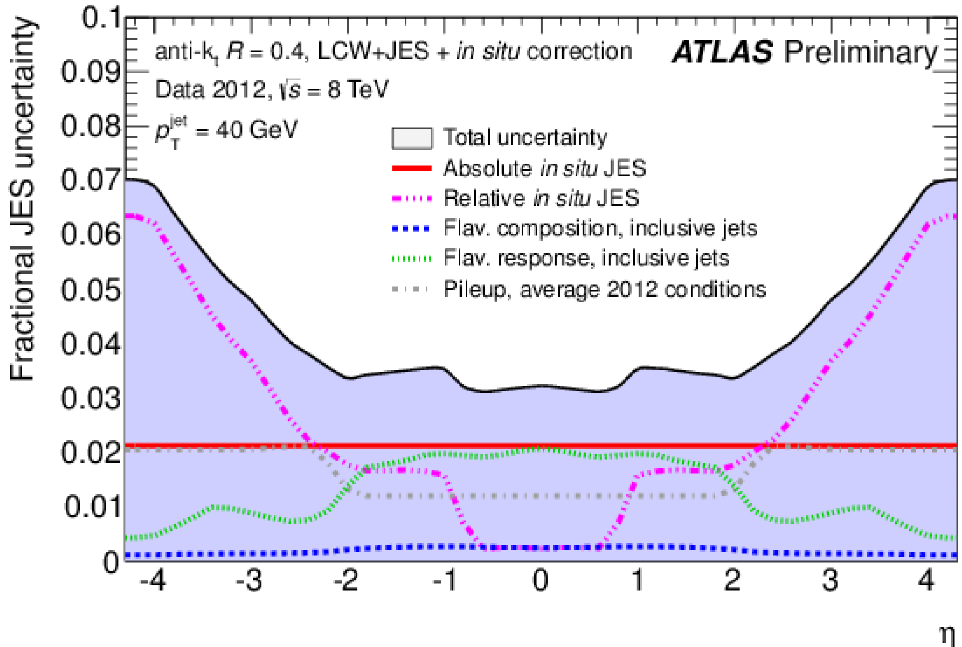




Systematic uncertainties

- Jet energy scale and resolution dominant at high $\Delta y(jj)$
- Forward region dominated by jet η response dependence studied using di-jet events p_T balance (+ other in-situ techniques)
- Theoretical modeling also larger than statistical error



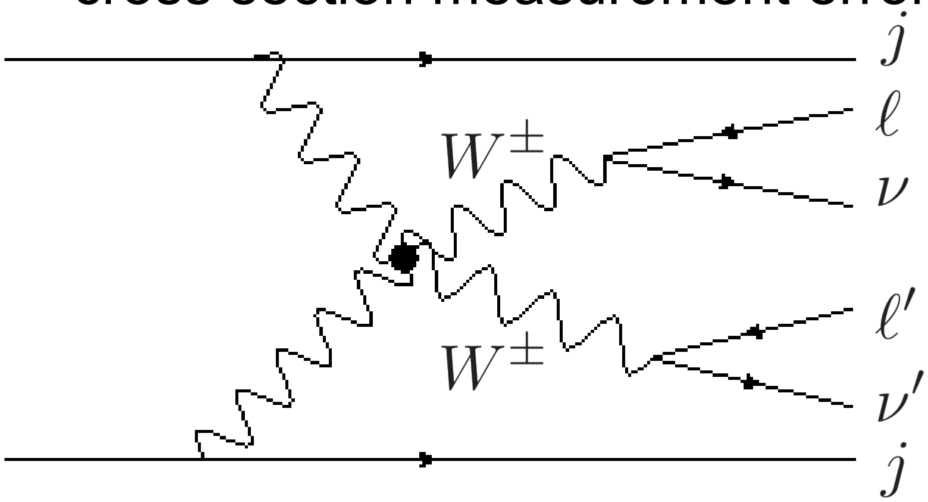


Caveat:Improved for current results

Outline

- Why studying vector boson scattering (VBS) at the LHC?
- Experimental challenge
- First evidence of $W^{\pm}W^{\pm}jj$
- Future prospects
- Conclusions

- Analyzed 20.3 fb^{-1} of p-p data @ $s^{1/2}$ = 8 TeV (2012 dataset)
- Target W leptonic decays: W → lν, l = e,μ
  - Hadronic modes: large W+jets and multi-jets background
- Signature (three final state channels): $e^{\pm}e^{\pm}jj$, $e^{\pm}\mu^{\pm}jj$, $\mu^{\pm}\mu^{\pm}jj$
  - Trigger with single electron or muon
- Simple counting experiment after selections optimized for best cross section measurement error



<u>Basic selections</u>

Two same-charge leptons

$$p_T(\ell) > 25 \text{ GeV}, \ |\eta| < 2.4$$

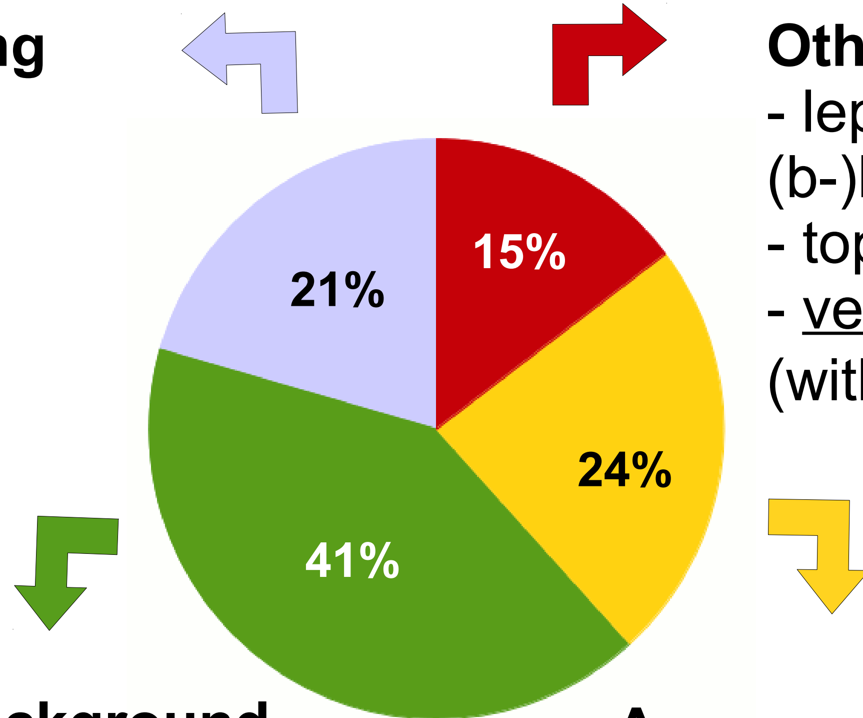
At least two jets

$$p_T(j) > 30 \text{ GeV}, |\eta| < 4.5$$

$$\not{E}_T > 40 \text{ GeV}$$

Sample composition and selections

$W^{\pm}W^{\pm}jj$ ewk+strong



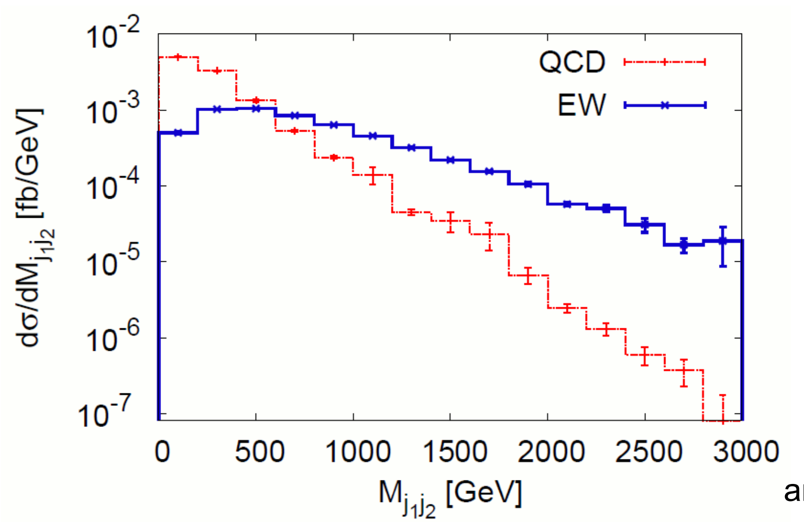
Other non-prompt
- leptons from (b-)hadron decays
- top, W+jets, multi-jets
- veto identified b-jets (within $|\eta| < 2.5$)

Prompt lepton background
- mainly WZ/γ^*, ZZ
- reduced requiring no third lepton with looser ID requirement and $p_T > 6(7)$ GeV for μ(e)

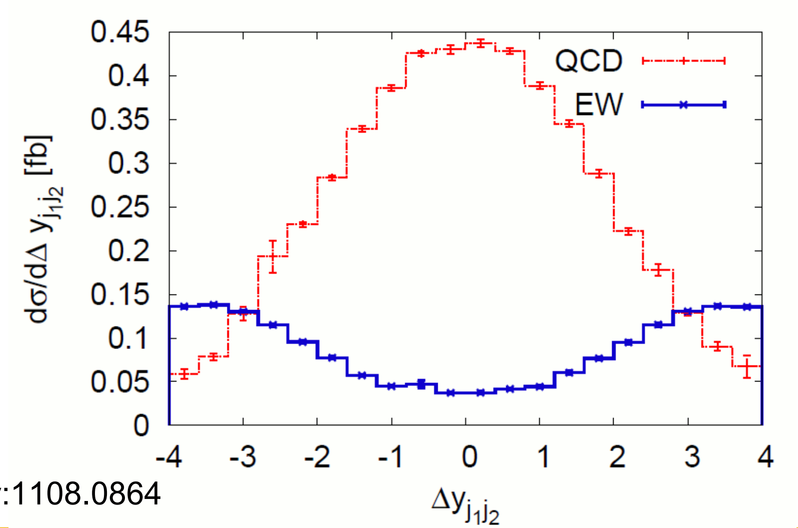
Asym. conversions ($\gamma \rightarrow ee$)
- $W\gamma$, lepton bremsstrahlung (mostly Drell-Yan, top)
- affects mostly ee channel
- $|m(ee) - m(Z)| > 10$ GeV

Signal regions and goals

- m(jj) > 500 GeV → **Inclusive signal region**
  - Measure $W^{\pm}W^{\pm}jj$ production cross section (electroweak+strong)
  - Expected SM $\sigma^{fid}(WWjj) = 1.52 \pm 0.11$ fb
- In addition, require $|\Delta y(jj)| > 2.4$ → **VBS signal region**
  - Measure electroweak WWjj (strong WWjj as background)
  - Expected SM $\sigma^{fid}(WWjj\text{-}ewk) = 0.95 \pm 0.06$ fb



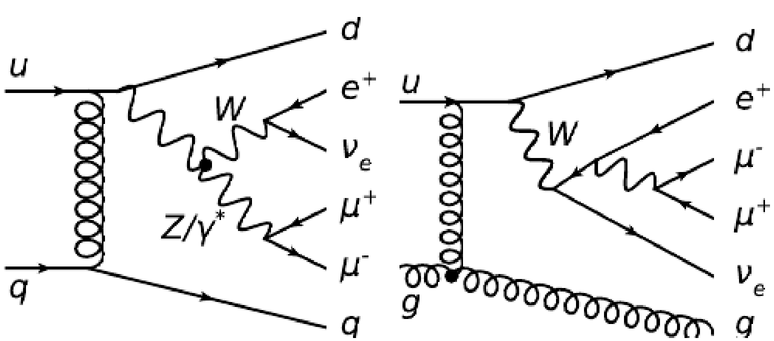
arXiv:1108.0864



Prompt leptons background

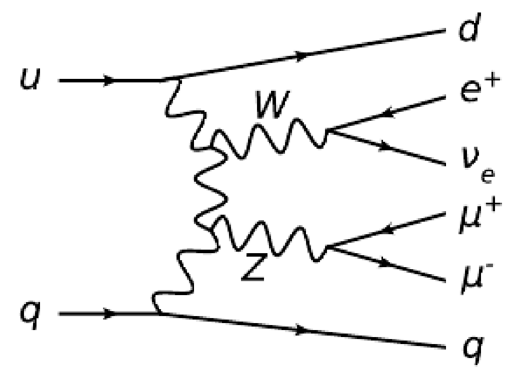
- WZ/γ*+jets – one lepton out of acceptance or not reconstructed
  - About 30% from off-shell Z or γ* after selections
  - Offshell W and W → lllν decays (Z radiation) suppressed
- Estimated using simulation: total theory uncertainty ~14%
  - could be reduced with parton-shower interface for NLO calculation

Strong WZ/γ* production



75% of all prompt-background
arXiv:hep-ph/0701105

Electroweak WZ/γ* production

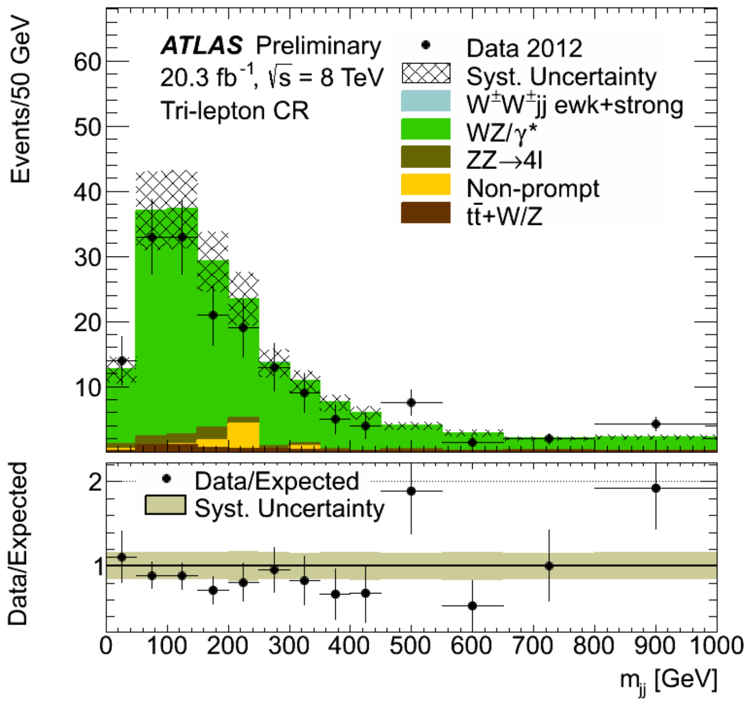


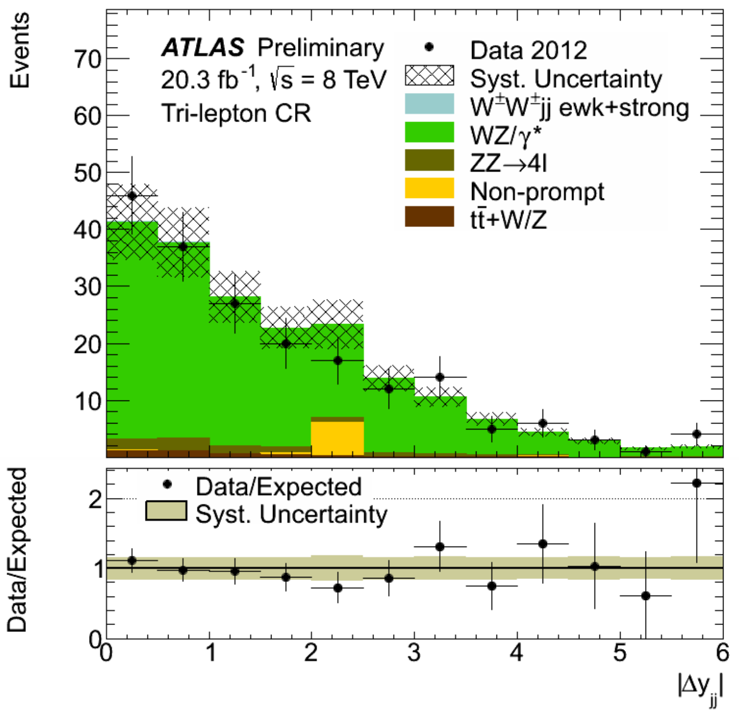
15% of all prompt-background
arXiv:1305.1623

Prompt leptons background

- ZZ+jets, tt+W/Z, tZj contribute together less than 10%
- Test in control region:
  - 3-leptons: test jets modeling
  - lower jet multiplicities:
    test lepton efficiency modeling

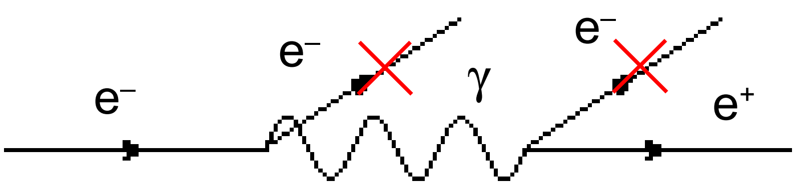
Tri-lepton			
Channel	Expected	Observed	$\frac{(Exp-Obs)}{\sigma(stat+syst)}$
ee$+\ell$	36±6	40	-0.5
e$\mu+\ell$	110±18	104	0.3
$\mu\mu+\ell$	60±10	48	0.9





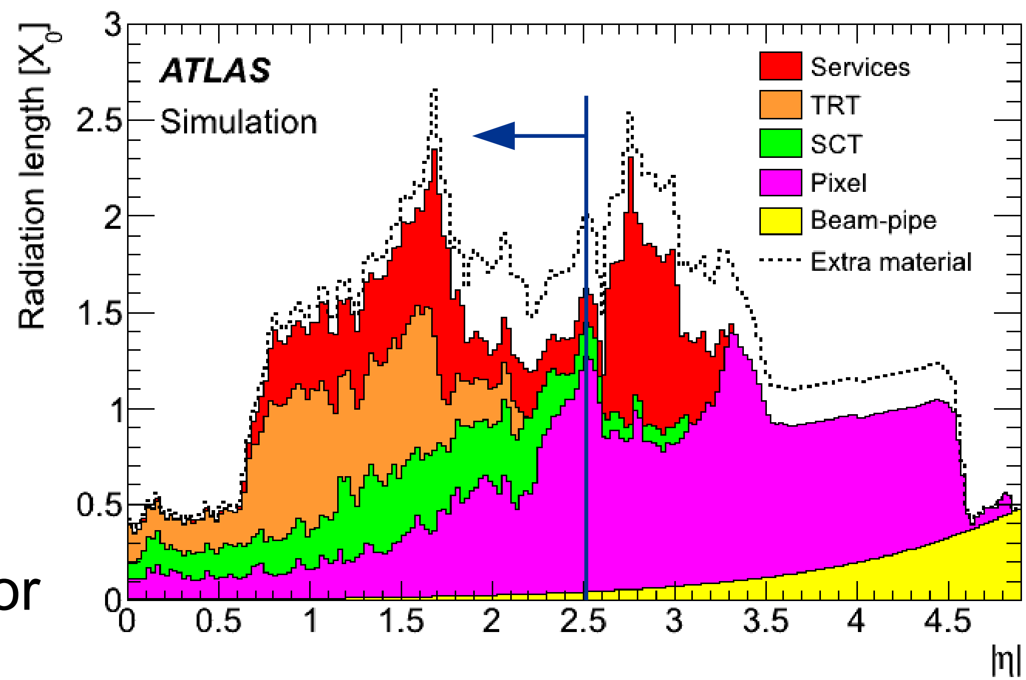
Background from conversions

- Two main contributors
  - Z/γ*+jets, tt, di-boson producing opposite-charge leptons with charge “mis-measured” → data-driven
  - Wγ jj production → simulation
- Both share the same dominant mechanism for passing analysis selections: γ conversion



 = not reconstructed

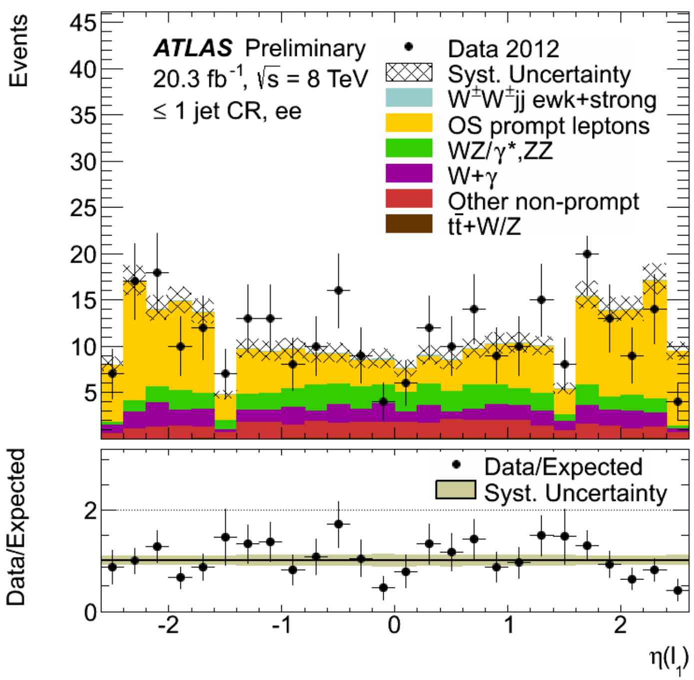
- Conversion rate depends on material in the (inner) detector

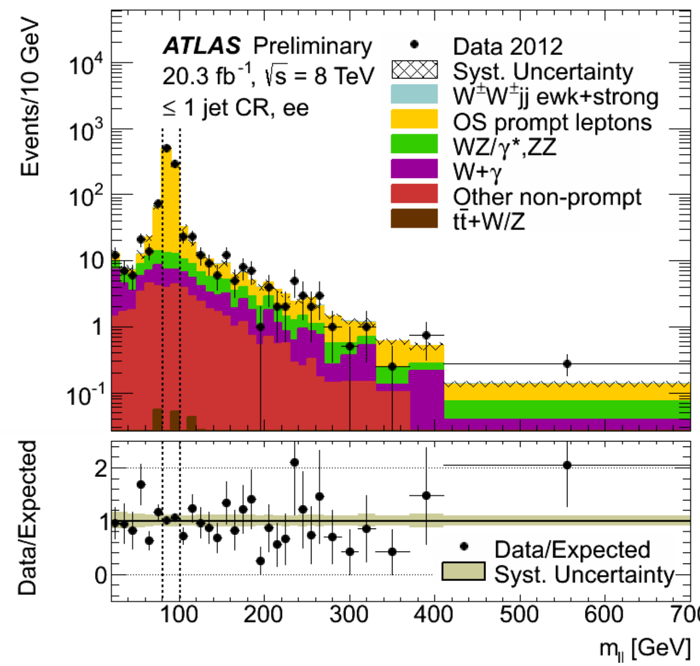


Opposite-charge leptons

- Measure charge mis-measurement rate using $Z \rightarrow ee$
- Select data with all selections but oppositely charged leptons
- Weight events based on charge mis-measurement rate
- Test in control region with low jet multiplicity

≤1 jet			
Channel	Expected	Observed	$\frac{(Exp-Obs)}{\sigma(stat+syst)}$
ee	278±28	288	-0.3
$e\mu$	288±42	328	-0.9
$\mu\mu$	88±14	101	-0.8



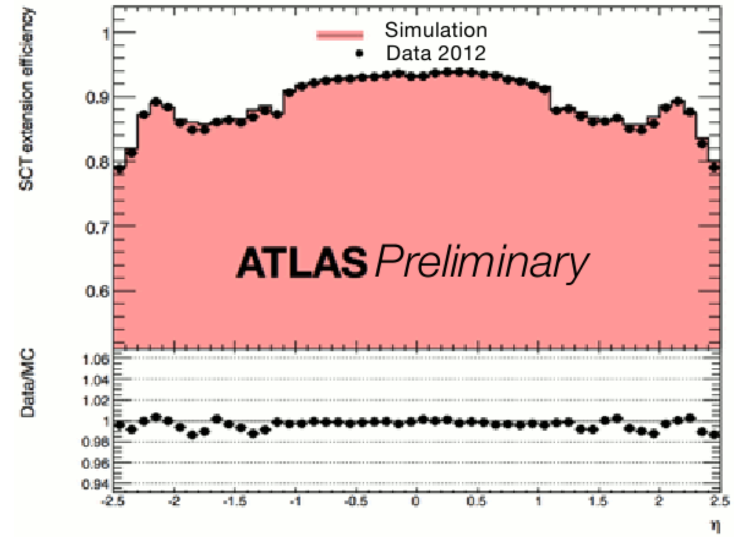


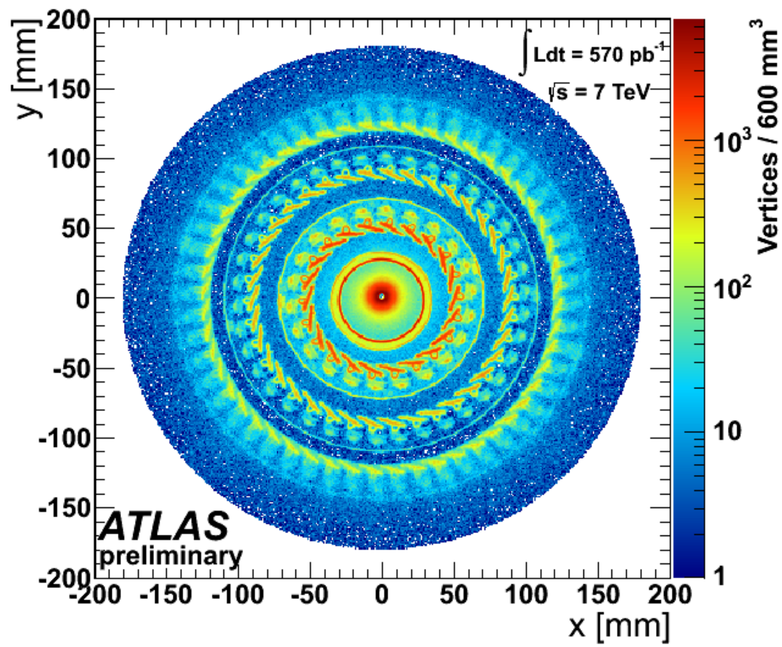
Constraining material in the ID

- For estimates based on simulation need to assess material modeling
- Careful estimation of material established in the beginning...

Sub-detector	Measured weight (kg)	Weight in simulation (kg)
SCT barrel	201±20	222
TRT barrel	707±20	700
SCT+TRT barrel	883±20	922

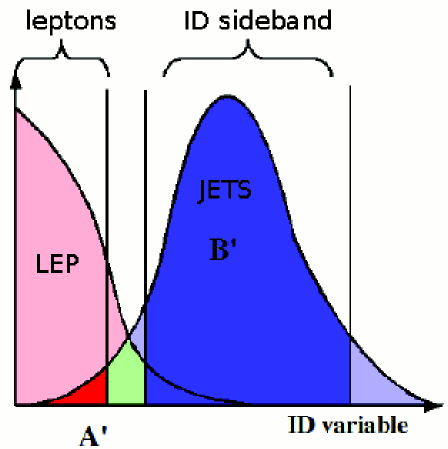
- ...and refined with collision data
  - Particularly important for **local** mis-modeling in simulation
- Methods accurate to 5-10% of X_0
- ~1.8M volumes in GEANT simulation

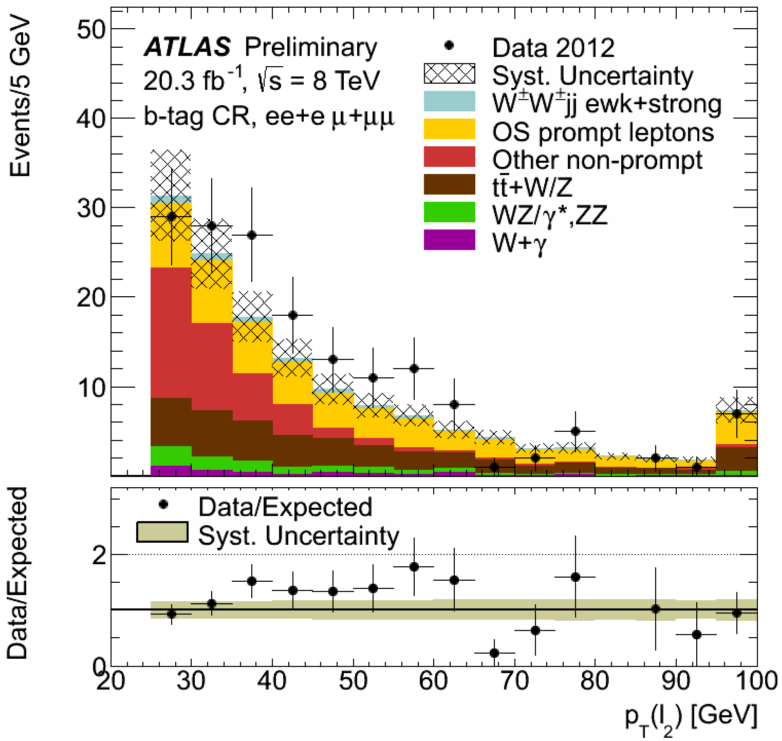




Other non-prompt leptons

- **Mainly from (b-)hadrons decays (e.g. $t\bar{t}$)**
  - Use sidebands in lepton isolation to extrapolate contribution in signal regions
  - Extrapolation factor measured in di-jet sample
  - sample-dependence systematic from simulation





- **Total uncertainty 40-50%**
- **Test modeling in fake lepton enriched sample**
  - Invert b-jet veto

b−tagged			
Channel	Expected	Observed	$\frac{(Exp-Obs)}{\sigma(stat+syst)}$
ee	40±6	46	-0.7
$e\mu$	75±13	82	-0.4
$\mu\mu$	25±7	36	-1.3

Summary of systematics

Summary of the effect of main systematic uncertainties on total background/signal expectation

Relative systematic uncertainty (%)		
Source	Total background	Total signal
Jet uncertainties	11-13	6
Theory	6-11	6-7
Others	10-13	4-6
Total systematic	18-20	10-11

- **Dominant experimental systematic from Jet Energy scale and resolution**
  - Lepton reconstruction efficiencies well under control
- **Large uncertainties on non-prompt leptons backgrounds does not play a dominant role since their expected contribution is small**

Summary of systematics

Summary of the effect of main systematic uncertainties on total background/signal expectation

Relative systematic uncertainty (%)		
Source	Total background	Total signal
Jet uncertainties	11-13	6
Theory	6-11	6-7
Others	10-13	4-6
Total systematic	18-20	10-11

- **Theory uncertainties important**
  - Dominated by WZ/γ^* uncertainty for backgrounds
    - Parton-shower uncertainties important: lacking a NLO calculation which can be interfaced to parton-shower MC

Summary of systematics

Summary of the effect of main systematic uncertainties on total background/signal expectation

Relative systematic uncertainty (%)		
Source	Total background	Total signal
Jet uncertainties	11-13	6
Theory	6-11	6-7
Others	10-13	4-6
Total systematic	18-20	10-11

- **Expected statistical uncertainty on cross section measurement: 30-40%**
- **Systematics to play a much more important role in the (not so far) future**

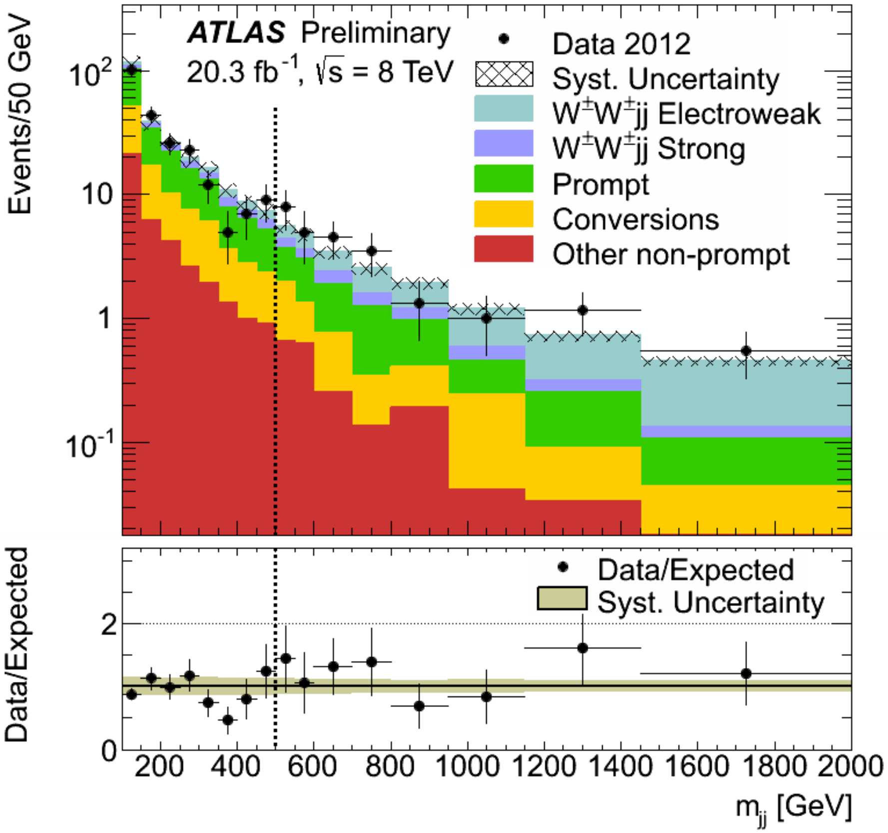
Signal regions

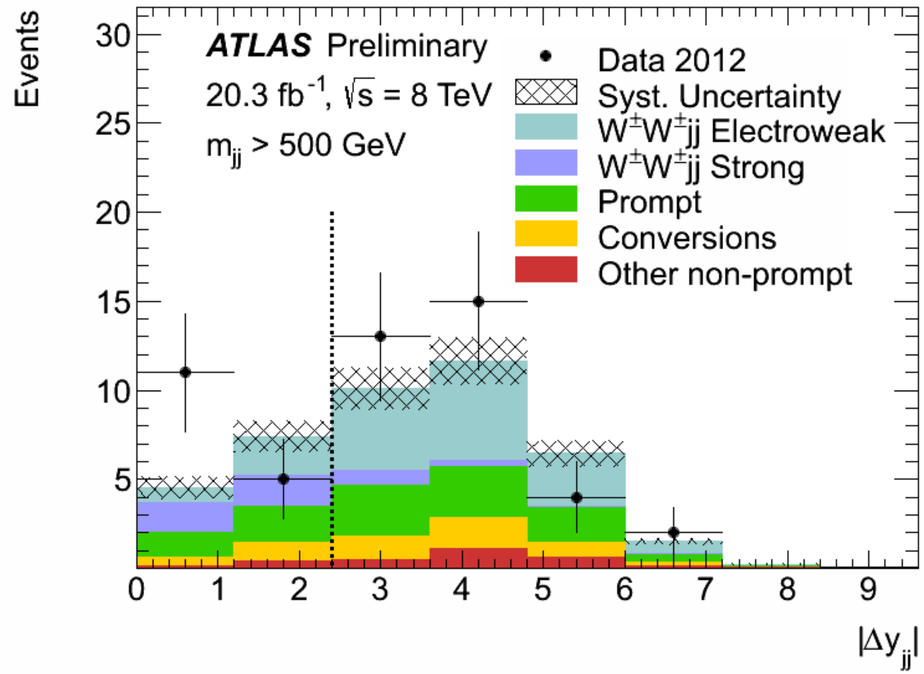
- Observed yields consistent with SM signal expectation

	Inclusive Region			VBS Region		
	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$
Prompt	3.0 ± 0.7	6.1 ± 1.3	2.6 ± 0.6	2.2 ± 0.5	4.2 ± 1.0	1.9 ± 0.5
Conversions	3.2 ± 0.7	2.4 ± 0.8	–	2.1 ± 0.5	1.9 ± 0.7	–
Other non-prompt	0.61 ± 0.30	1.9 ± 0.8	0.41 ± 0.22	0.50 ± 0.26	1.5 ± 0.6	0.34 ± 0.19
$W^{\pm}W^{\pm}jj$ Strong	$\mathbf{0.89} \pm \mathbf{0.15}$	$\mathbf{2.5} \pm \mathbf{0.4}$	$\mathbf{1.42} \pm \mathbf{0.23}$	0.25 ± 0.06	0.71 ± 0.14	0.38 ± 0.08
$W^{\pm}W^{\pm}jj$ Electroweak	$\mathbf{3.07} \pm \mathbf{0.30}$	$\mathbf{9.0} \pm \mathbf{0.8}$	$\mathbf{4.9} \pm \mathbf{0.5}$	$\mathbf{2.55} \pm \mathbf{0.25}$	$\mathbf{7.3} \pm \mathbf{0.6}$	$\mathbf{4.0} \pm \mathbf{0.4}$
Total background	6.8 ± 1.2	10.3 ± 2.0	3.0 ± 0.6	5.0 ± 0.9	8.3 ± 1.6	2.6 ± 0.5
Total signal	$\mathbf{4.0} \pm \mathbf{0.4}$	$\mathbf{11.4} \pm \mathbf{1.2}$	$\mathbf{6.3} \pm \mathbf{0.7}$	$\mathbf{2.55} \pm \mathbf{0.25}$	$\mathbf{7.3} \pm \mathbf{0.6}$	$\mathbf{4.0} \pm \mathbf{0.4}$
Total predicted	10.7 ± 1.4	21.7 ± 2.6	9.3 ± 1.0	7.6 ± 1.0	15.6 ± 2.0	6.6 ± 0.8
Data	12	26	12	6	18	10

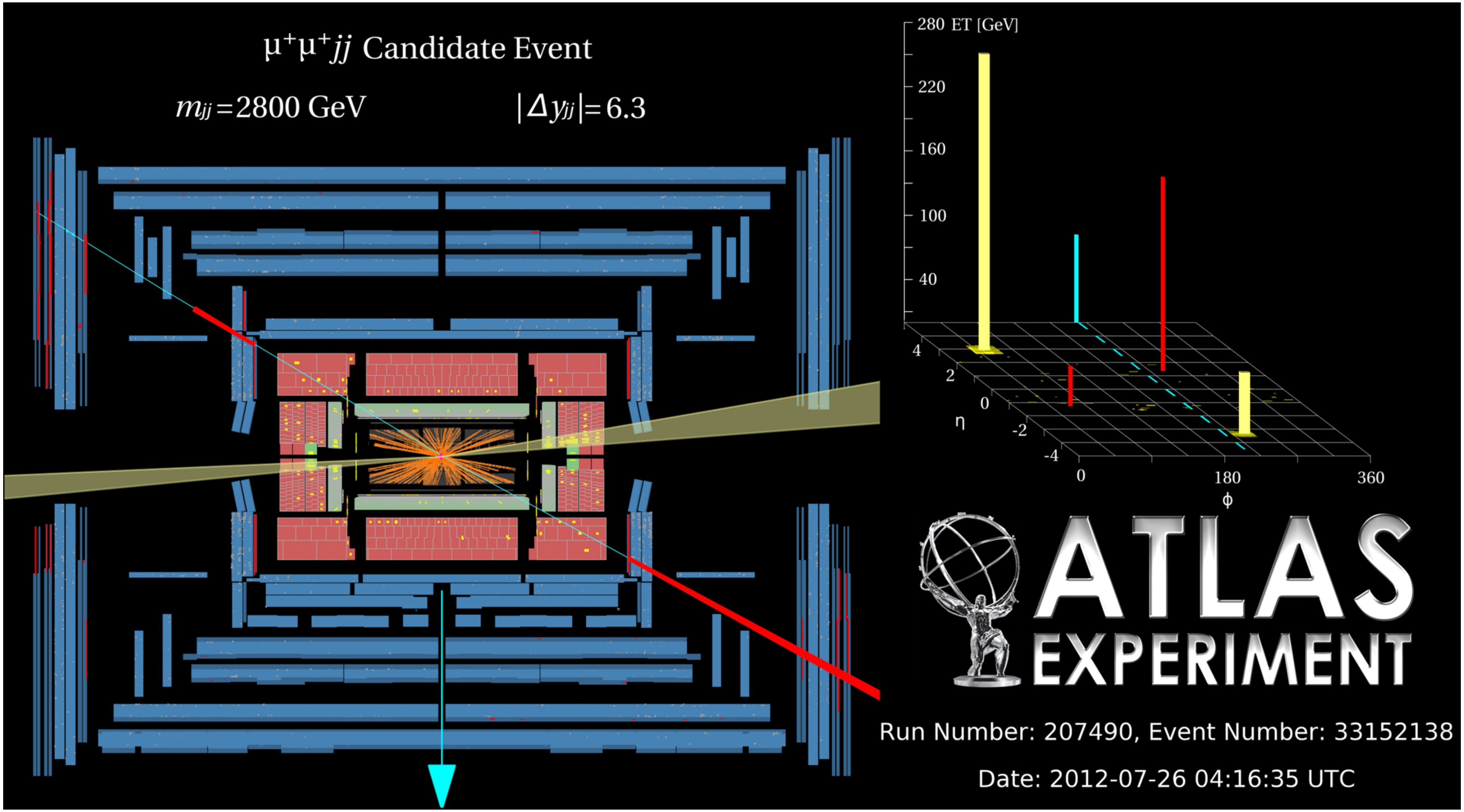
- Observed (expected) significance over background-only hypothesis:
  - **4.5σ** (3.4σ) for electroweak+strong $W^{\pm}W^{\pm}jj$ in Inclusive Region
  - **3.6σ** (2.8σ) for electroweak $W^{\pm}W^{\pm}jj$ in VBS Region
- **First evidence of electroweak $W^{\pm}W^{\pm}jj$ production**

- Kinematics of excess consistent with SM expectation





Data event with largest $\Delta y(jj)$ (and $m(jj)$)



Cross section measurement

- Measure fiducial cross sections in a phase space that closely mimic experimental selections (= fiducial regions)

$$\sigma^{\text{fid.}} = \frac{N^{\text{obs.}} - N^{\text{bkg}}}{\mathcal{L} \cdot \epsilon}$$

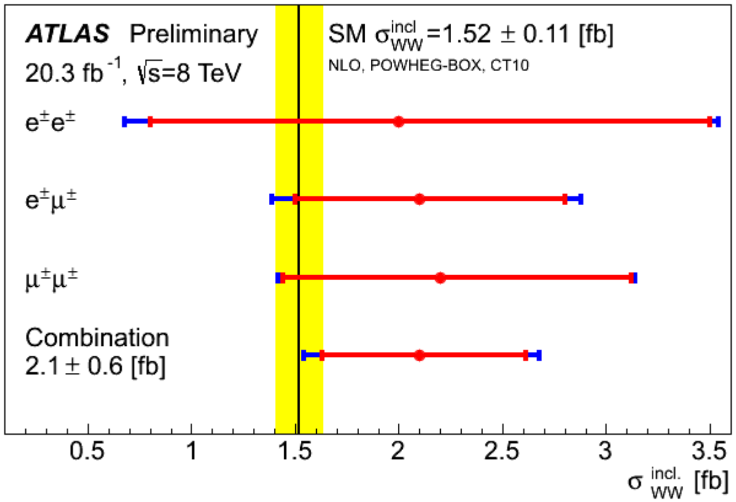
$$\epsilon = \frac{N_{\text{signal region, reco-level}}}{N_{\text{fiducial region, particle-level}}}$$

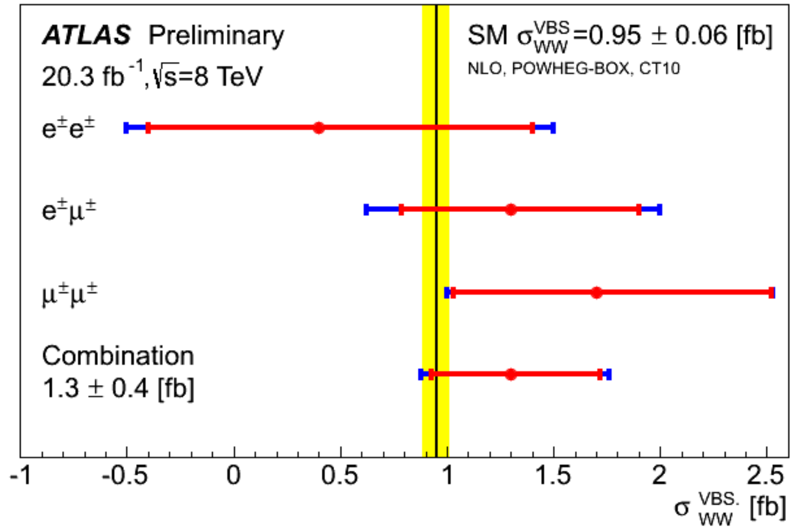
Estimated using full detector simulation
Trigger efficiency
Object reconstruction efficiency
Migration in/out of fiducial phase space

- Fiducial regions includes W decay branching ratios to $e\nu$, $\mu\nu$
  - Efficiency ε also corrects for $\tau \rightarrow e,\mu+X$ contribution (~10% of expected signal)

- Cross section measured for each channel and combined

First W±W±jj cross section measurement





		Measurement	SM Expectation
$\sigma^{\text{fid, Inclusive Region}}_{W^\pm W^\pm jj}$	=	$2.1 \pm 0.5(\text{stat}) \pm 0.3(\text{syst.})$ fb	1.52 ± 0.11 fb
$\sigma^{\text{fid, VBS Region}}_{W^\pm W^\pm jj\ \text{Electroweak}}$	=	$1.3 \pm 0.4(\text{stat}) \pm 0.2(\text{syst.})$ fb	0.95 ± 0.06 fb

anomalous Quartic Gauge Coupligs

- Using electroweak $W^{\pm}W^{\pm}jj$ fiducial cross section in VBS phase space to constrain aQGC
- Effective field theory approach

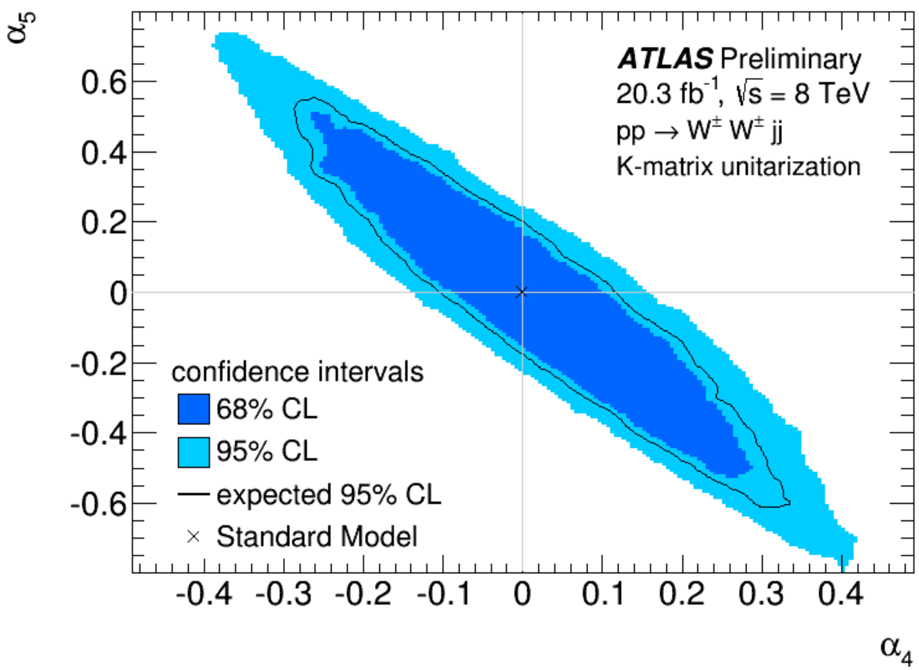
$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_{\text{dimension d}} \sum_i \frac{c_i^{(\mathrm{d})}}{\Lambda^{\mathrm{d}-4}} \mathcal{O}_i^{(\mathrm{d})}$$

  - Valid below energy scale Λ

- Some d=8 operators can be mapped to d=4, d=6 ones

d=4	**d=6**	**d=8**
WWWW, WWZZ	$WWZ\gamma, WW\gamma\gamma$	all VVVV
Chiral Lagrangian	“non-linear” formalism	“linear” formalism
$\boxed{\alpha_4, \alpha_5}$	a_0 / Λ^2, a_C / Λ^2	$f_{S,i} / \Lambda^4$, $f_{M,i} / \Lambda^4$, $f_{T,i} / \Lambda^4$
Appelquist et al. (1980)	Belanger et al. (1992)	Eboli et al. (2006)

aQGC results



1-D observed 95% C.L. limits:

$-0.14 < \alpha_4 < 0.16$ (α_5=0)

$-0.23 < \alpha_5 < 0.24$ (α_4=0)

- Simplified-model interpretation (arXiv:1307.8170) relates to energy scale of hypothetical contributing resonance:

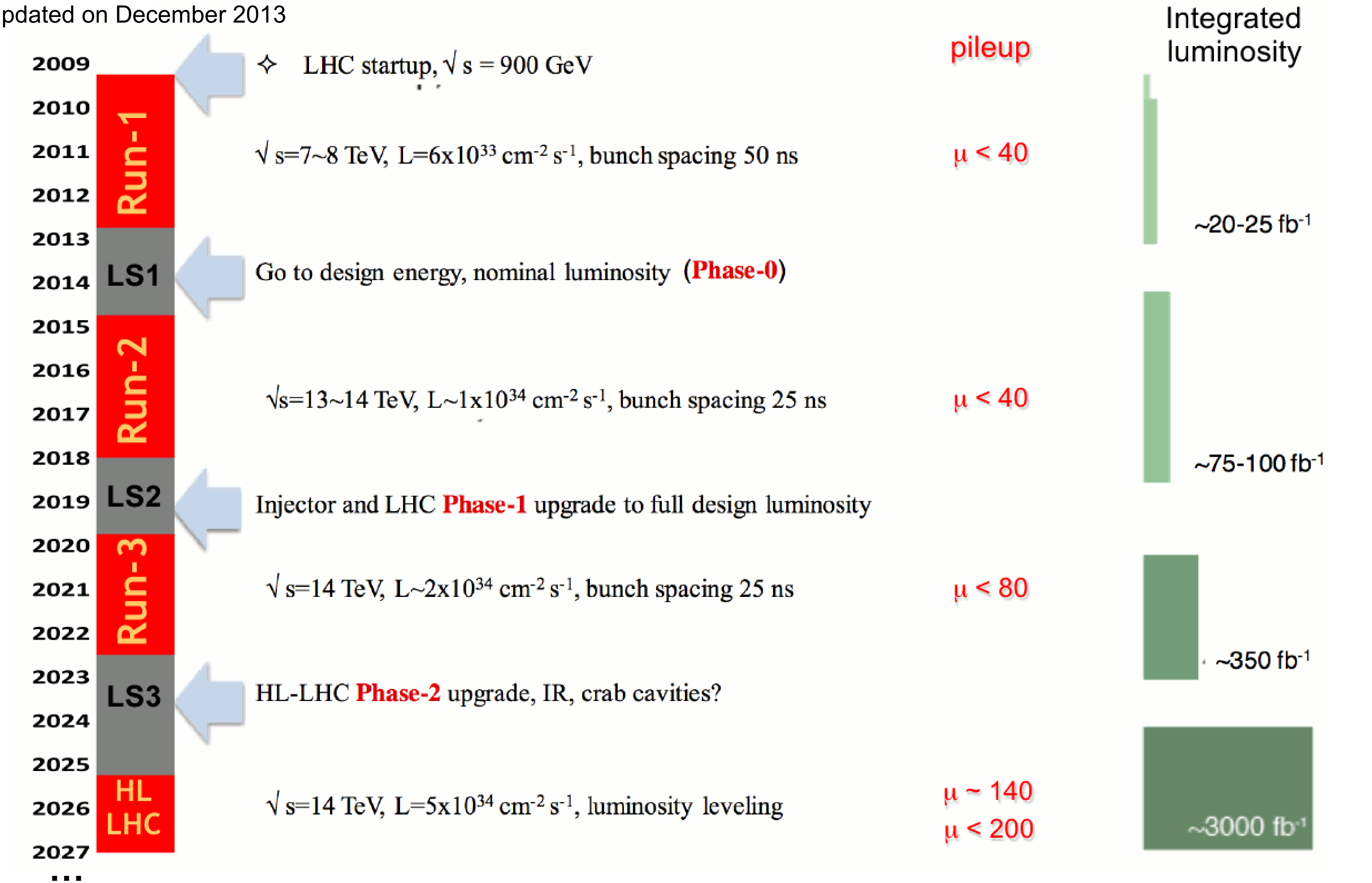
$$\Lambda = \frac{v}{\sqrt{\alpha_i}} \approx 500 - 650 \text{ GeV}$$

Outline

- Why studying vector boson scattering (VBS) at the LHC?
- Experimental challenge
- First evidence of $W^{\pm}W^{\pm}jj$
- **Future prospects**
- Conclusions

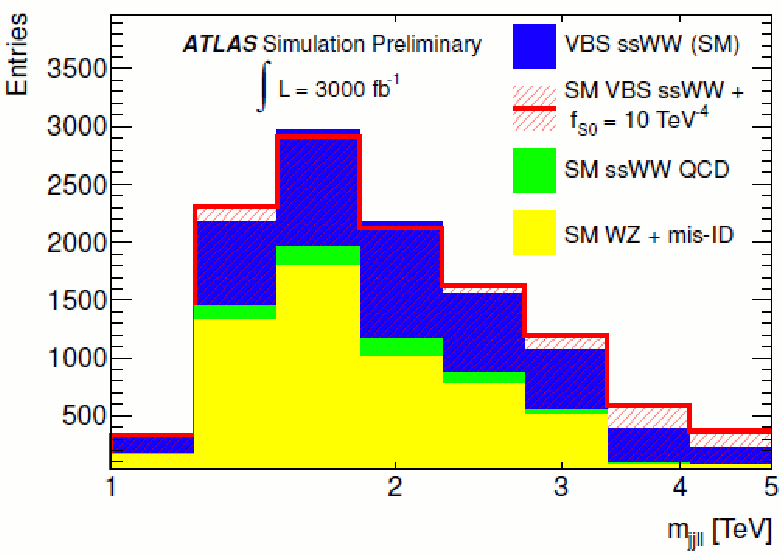
Future prospects

Updated on December 2013



$W^{\pm}W^{\pm}jj$ projections

- Sensitivity for 300/fb and 3000/fb (Snowmass studies)
  - simplified truth-based analysis [ATLAS-PHYS-PUB-2013-006]



Selection	Current	Projections
Two leptons $p_T >$ [GeV]	25	25
3rd lepton veto, $p_T >$ [GeV]	6(7)	25
Two jets, $p_T >$ [GeV]	30	50
$m(jj) >$ [GeV]	500	1000
$\lvert\Delta y(jj)\rvert >$	2.4	—

- Optimal jet p_T cut is tighter to reject (larger) pile-up contribution and because of stronger background rejection (good for larger statistics)
- Very rough background model: only accounts WZ/γ^* (scaled by 2)
- Results based on template fit of m(lljj) observable

$W^{\pm}W^{\pm}jj$: projection results

- Results can be interpreted in simplified models

arXiv:1310.6708,
arXiv:hep-ph/0606118

95% C.L. limits on broad resonance mass ($\Gamma \sim M$)			
Type of resonance	8 **TeV**, $20/fb$	14 TeV, $300/fb$	14 TeV, $3000/fb$
scalar	0.7 TeV	2.0 TeV	3.3 TeV
vector	0.9 TeV	2.6 TeV	4.4 TeV
tensor	1.2 TeV	3.5 TeV	6.0 TeV

using new results!

snowmass projections (arXiv:1310.6708)

- Both energy and luminosity increase play important roles
  - about a factor of 4 increase in cross section for both signal and main background from 8 TeV to 14 TeV

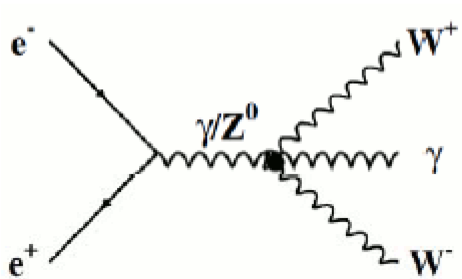
Conclusions

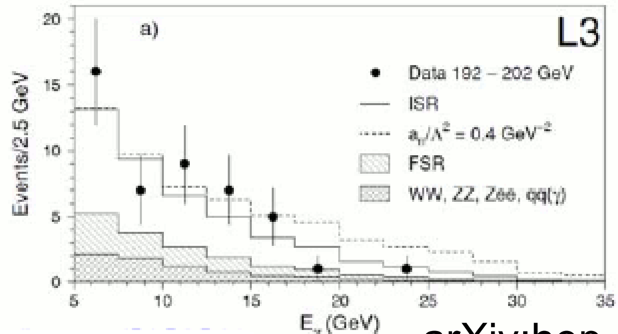
- **Vector boson scattering measurements offer an unique probe of quartic gauge interactions and Higgs sector**
  - complementary to direct Higgs couplings measurements
  - Usually very rare processes, difficult to observe
- **ATLAS has just reported the first evidence of electroweak production of $W^{\pm}W^{\pm}jj$**
  - milestone for a complete VBS program
  - First challenging probe of massive VVVV vertex
  - Experimental proof we can isolate these processes and keep backgrounds under control
- **Looking forward to fully explore the physics behind VBS in the next years of operations of the LHC!**

BACKUP

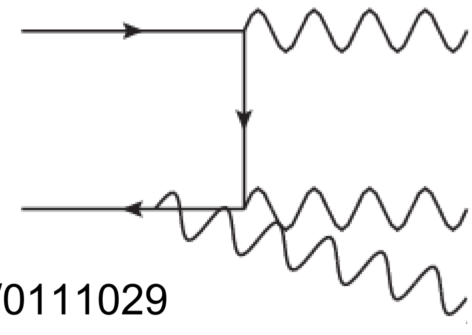
Study of quartic gauge couplings

- **Triple boson production (VVV)**
  - **LEP**: $e^+e^- \rightarrow W^+W^-\gamma$





Results consistent with ISR/FSR contribution (~96% @ $s^{1/2}$= 200 GeV)

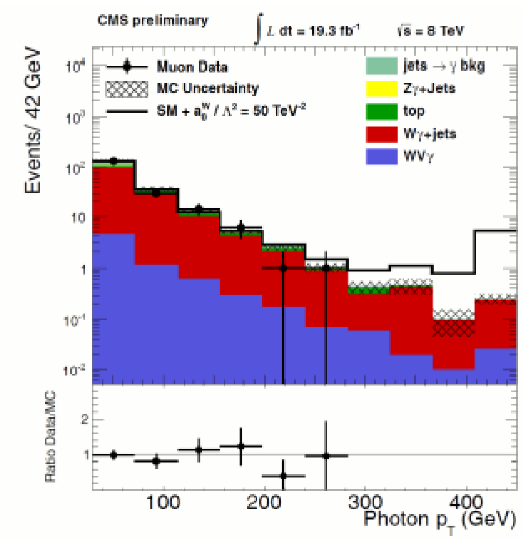


arXiv:hep-ex/0111029

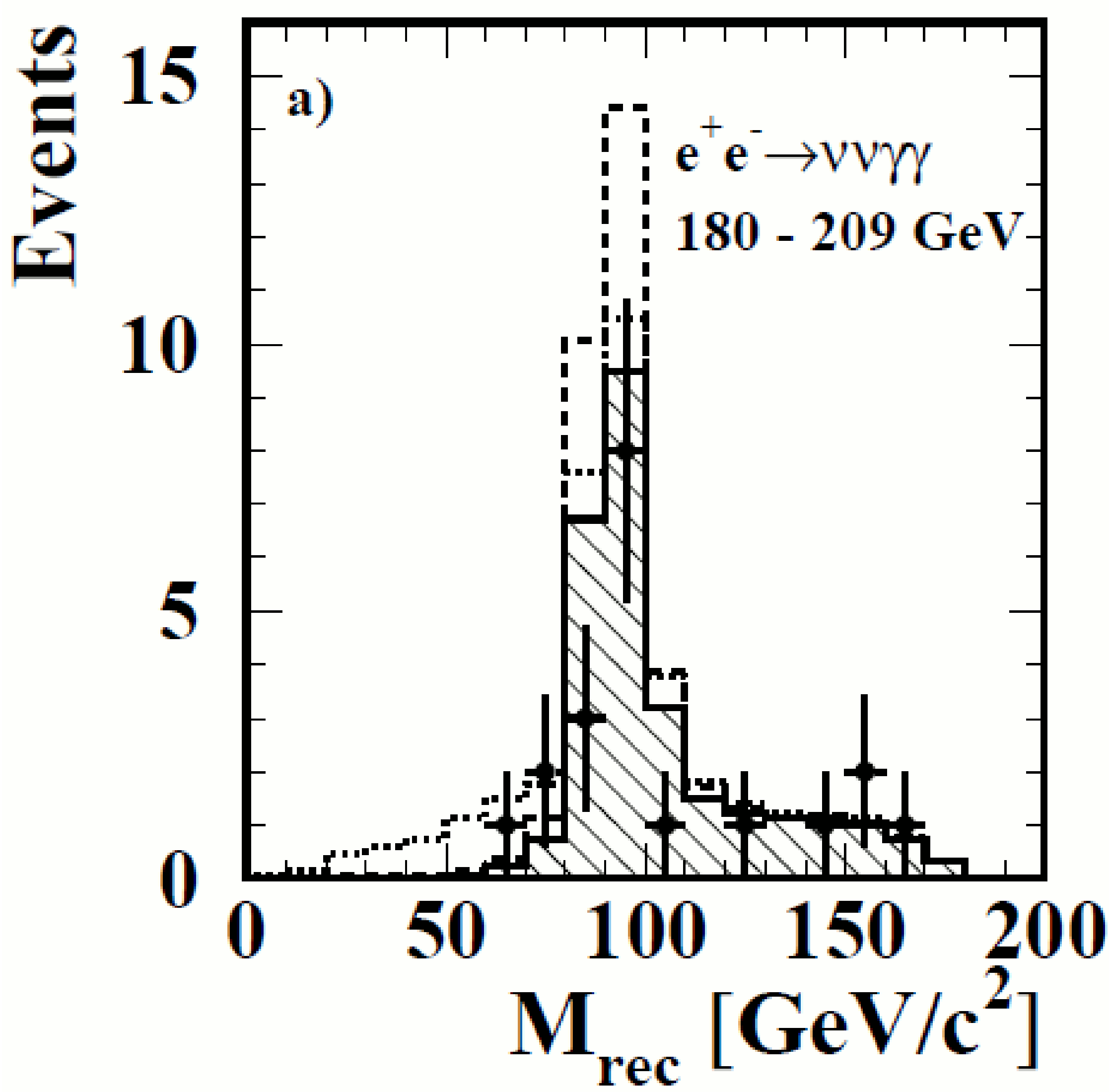
  - **LHC** (CMS): $pp \rightarrow W V \gamma$ (V = W, Z)
    - 19.3/fb of 8 TeV data
    - Sensitive to ~3.4xSM at 95%C.L.

CMS-PAS-SMP-13-009

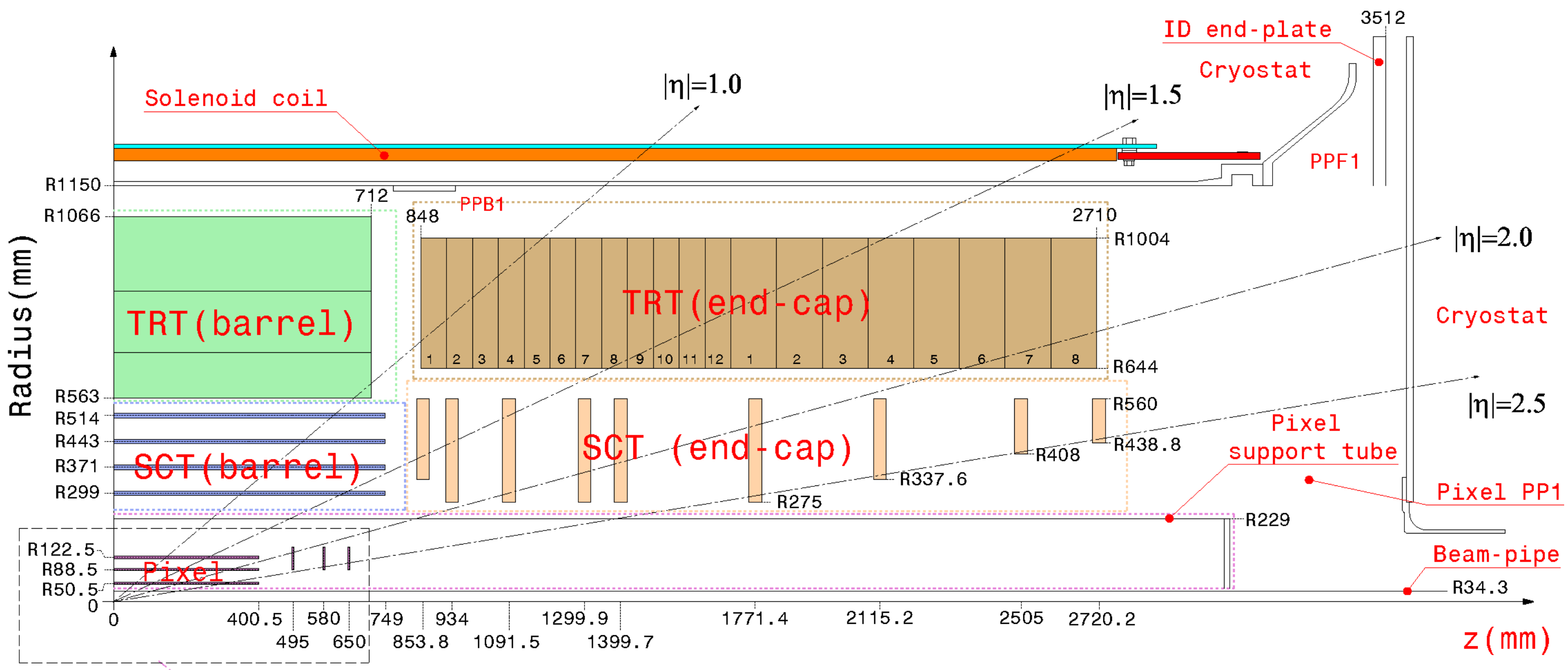
  - **LHC**: VH($\rightarrow$VV), V=W,Z
    - small contribution in Higgs results

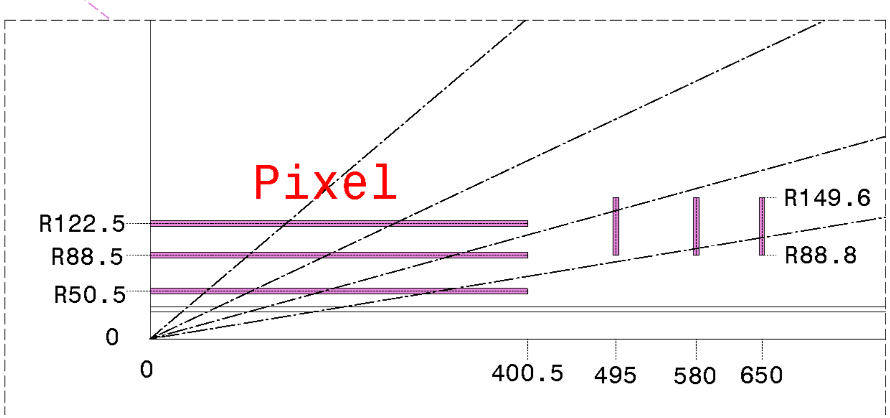


$e^+e^- \rightarrow \nu\bar{\nu}\gamma\gamma$, OPAL: M_{rec}



Inner detector quadrant





Envelopes

Pixel		45.5<R<242mm |Z|<3092mm
SCT barrel		255<R<549mm |Z|<805mm
SCT end-cap		251<R<610mm 810<|Z|<2797mm
TRT barrel		554<R<1082mm |Z|<780mm
TRT end-cap		617<R<1106mm 827<|Z|<2744mm

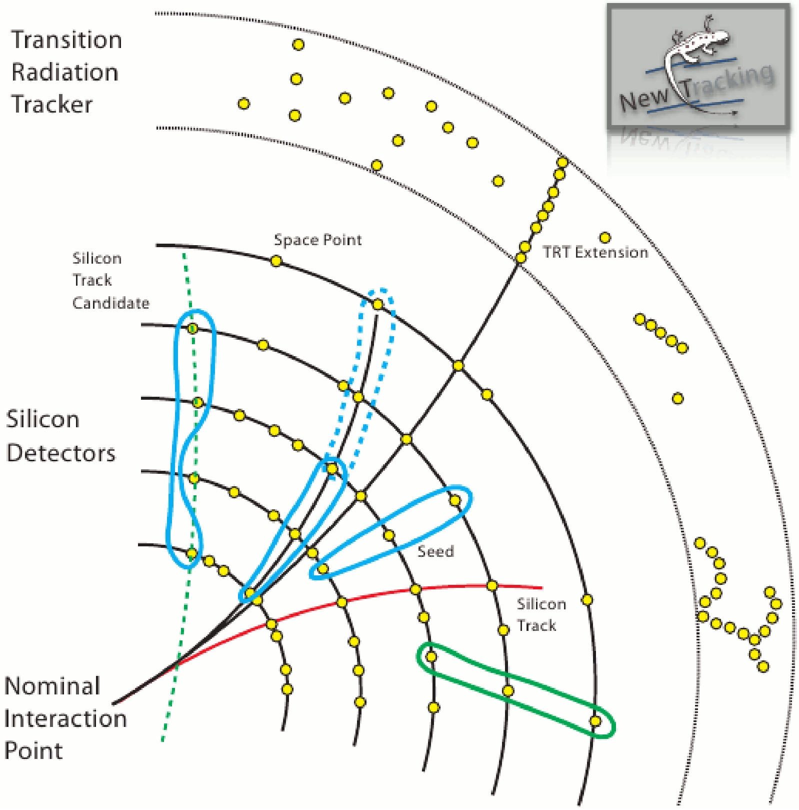
(simplified) charged particle reconstruction

Pre-processing of measurements (hits)
→ sub-detector dependent

track finder:
→ Inside-out combinatorial
→ start from pixel,SCT
→ extend to TRT
→ Recover TRT → Silicon and TRT standalone for secondaries

Precise **track fit/selection**
→ accounts for multiple scattering, energy loss
→ select best track candidates (hits, holes,..)

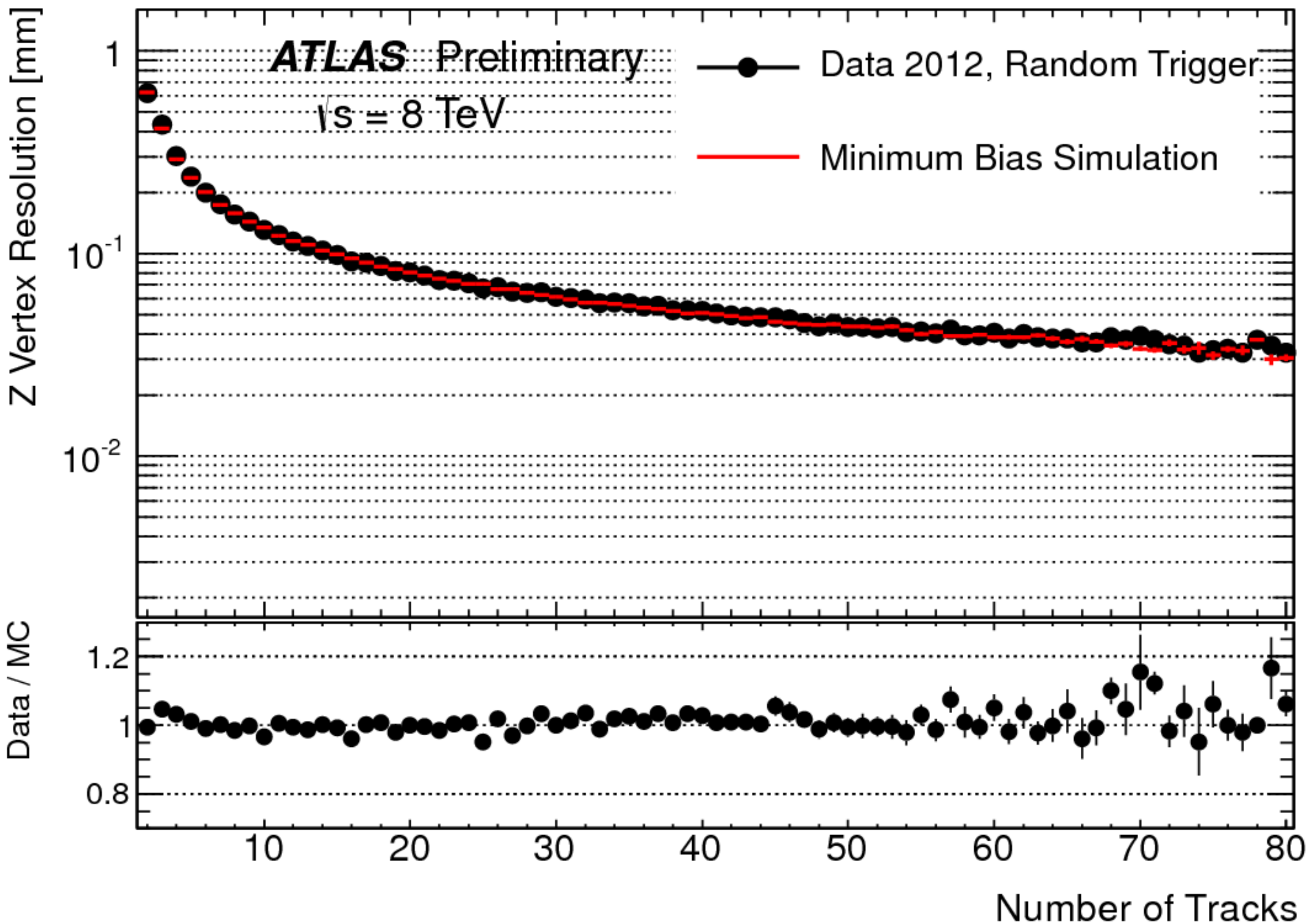
TRACKS



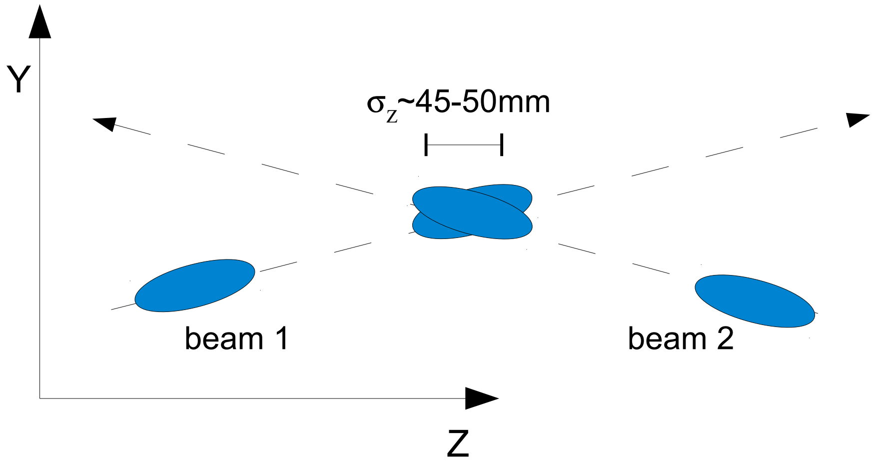
Primary vertex:
→ Iterative finding
→ Optimized for best position measurement
→ Robust agains outliers

Secondary vertex:
→ Photon conversions
→ b-hadrons decay
→ Explicit decay chains

Vertex Z resolution

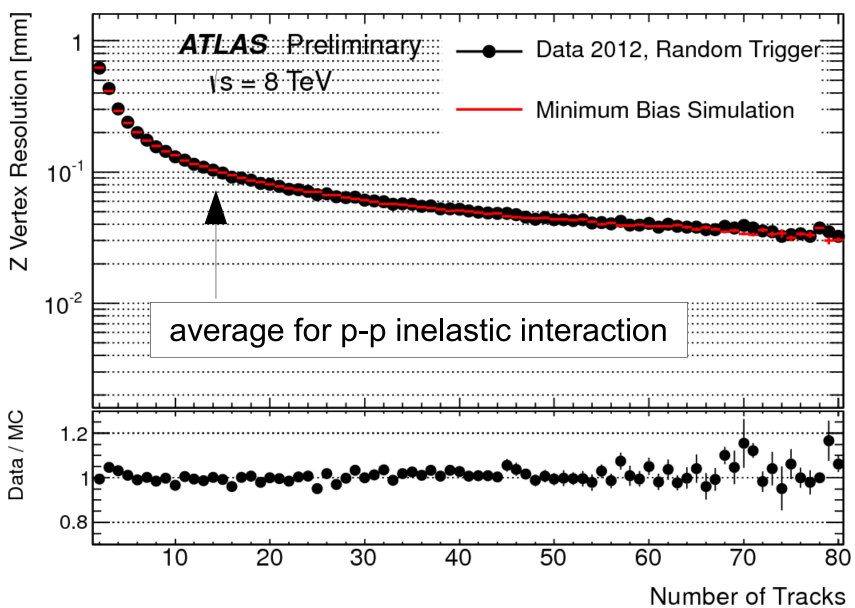


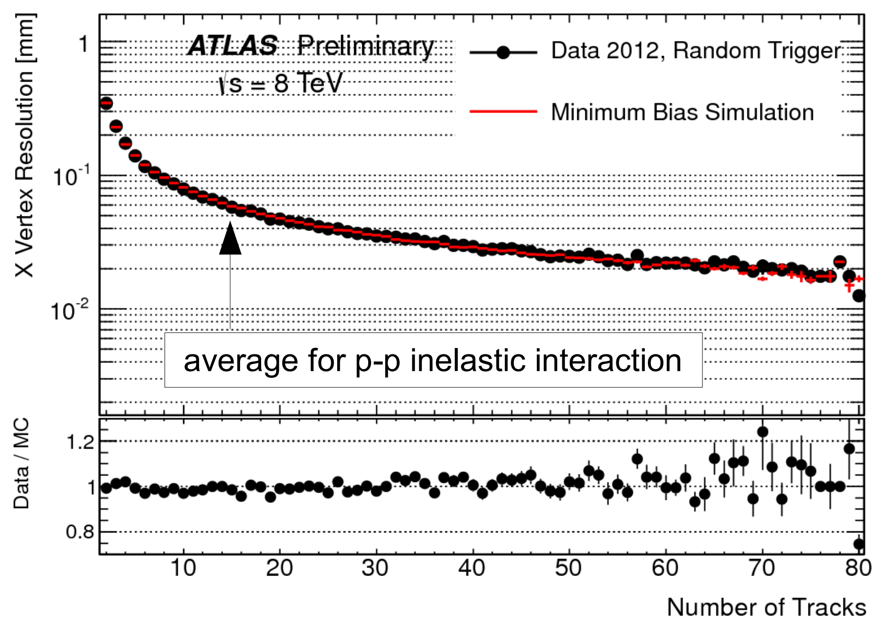
Distinguishing pile-up interactions



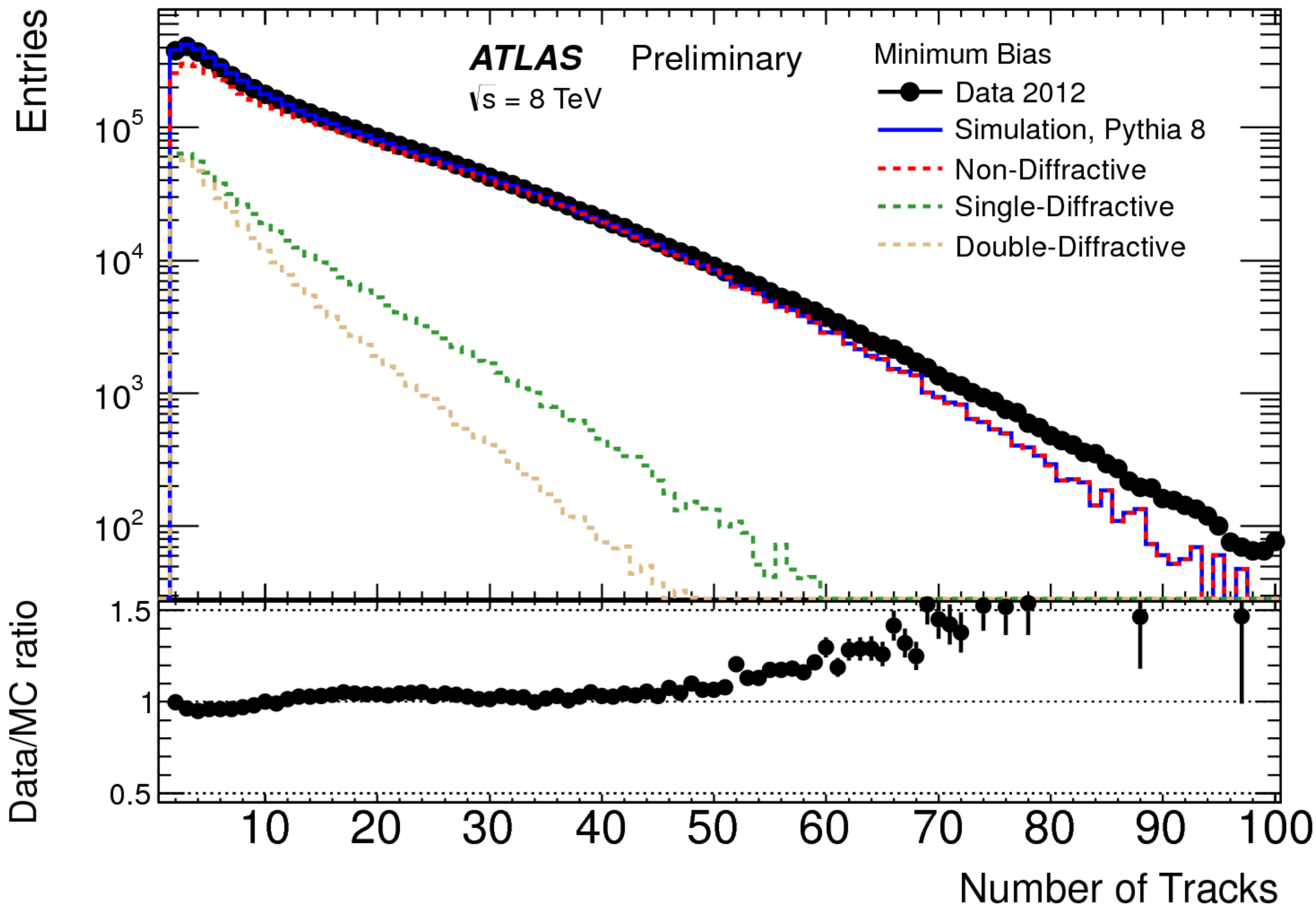
Interaction region (~Gaussian):
Transverse size (σ): 12-16μm
Longitudinal size (σ): 45-50mm

Transverse size << average vertex resolution
Distinguish interactions only along z



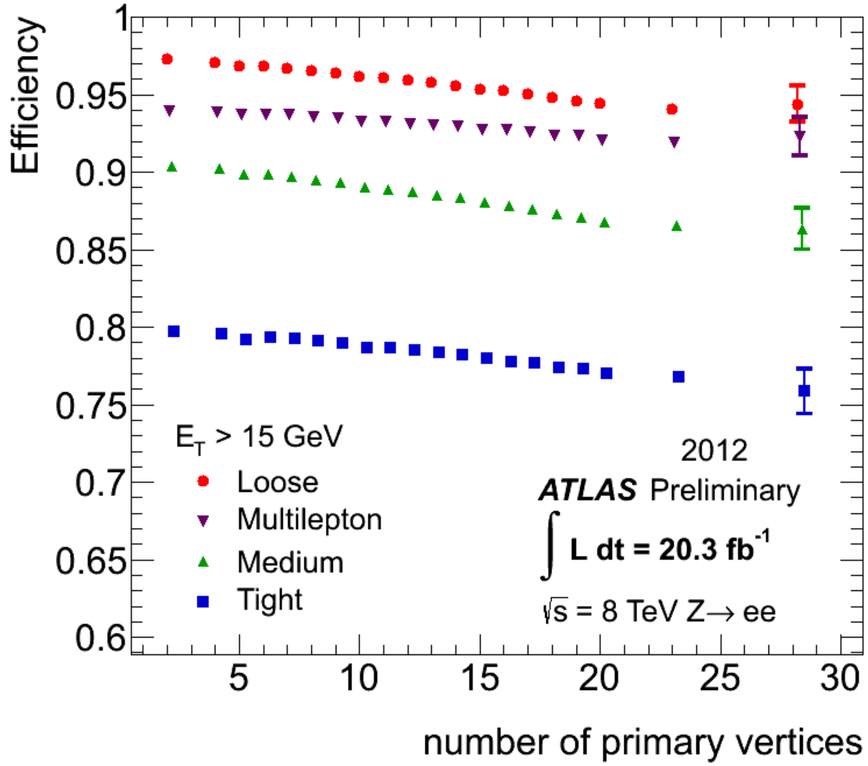


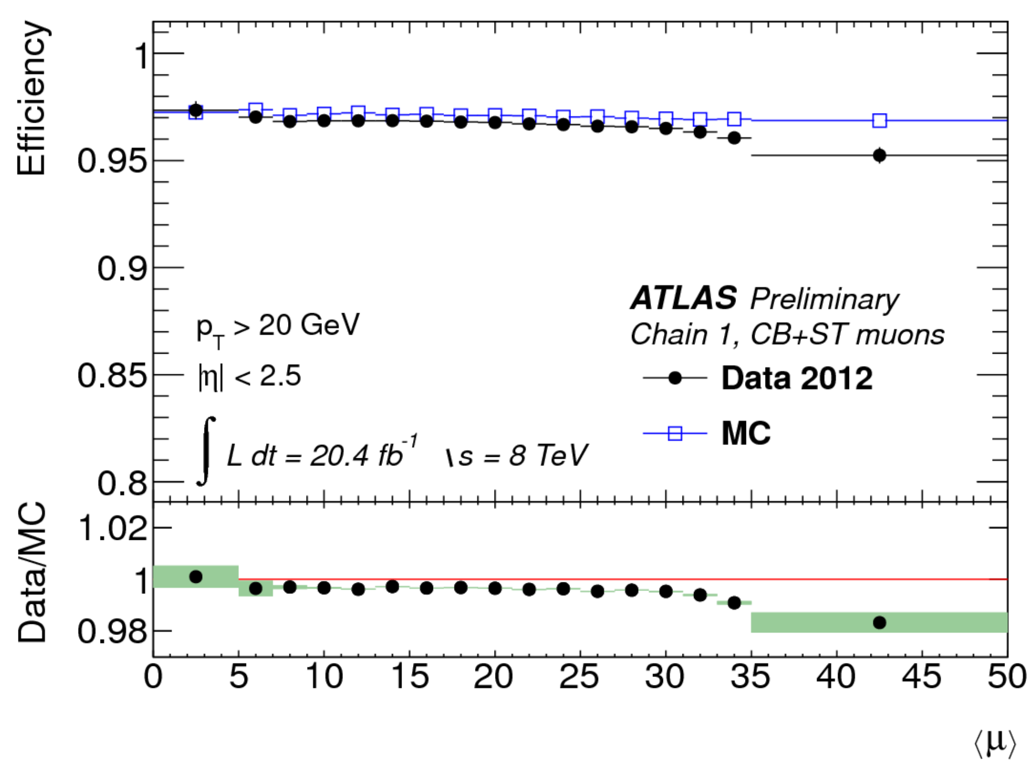
Track multiplicity, minimum-bias @ 8 TeV



Lepton reconstruction performance

- Lepton reconstruction and identification efficiency also tuned to be robust against pile-up
  - residual dependence well reproduced in simulation





Jet energy corrections

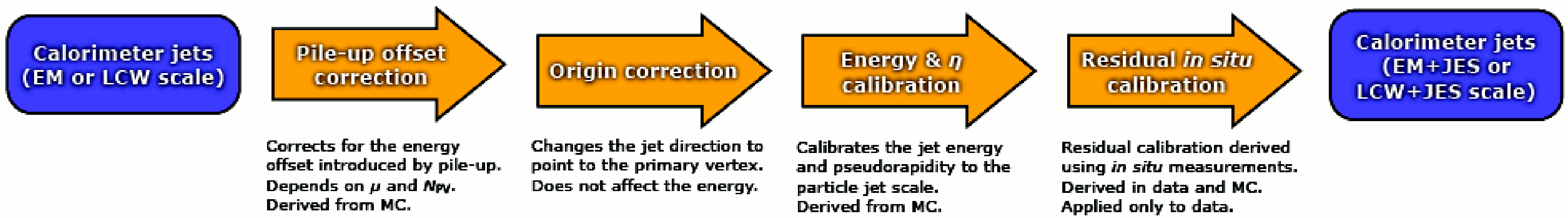
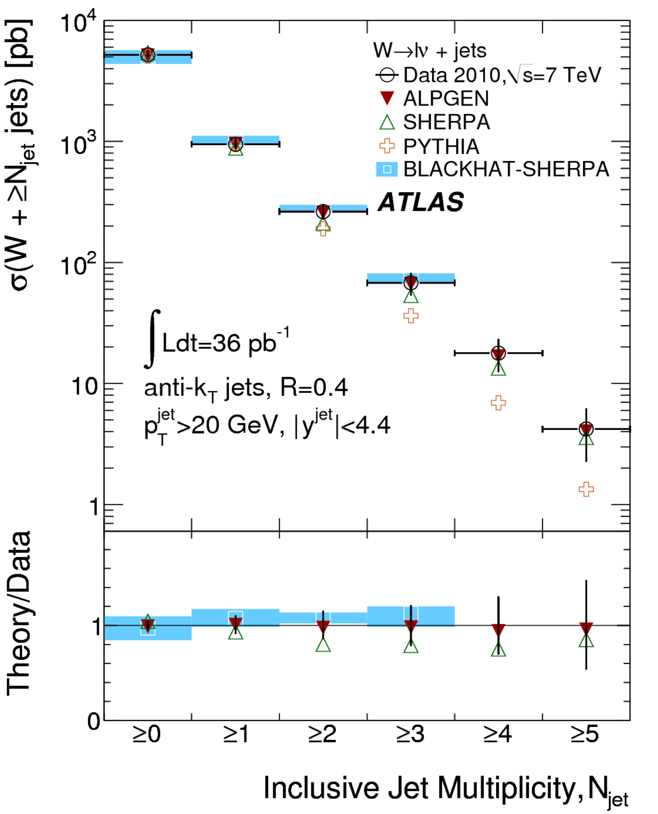
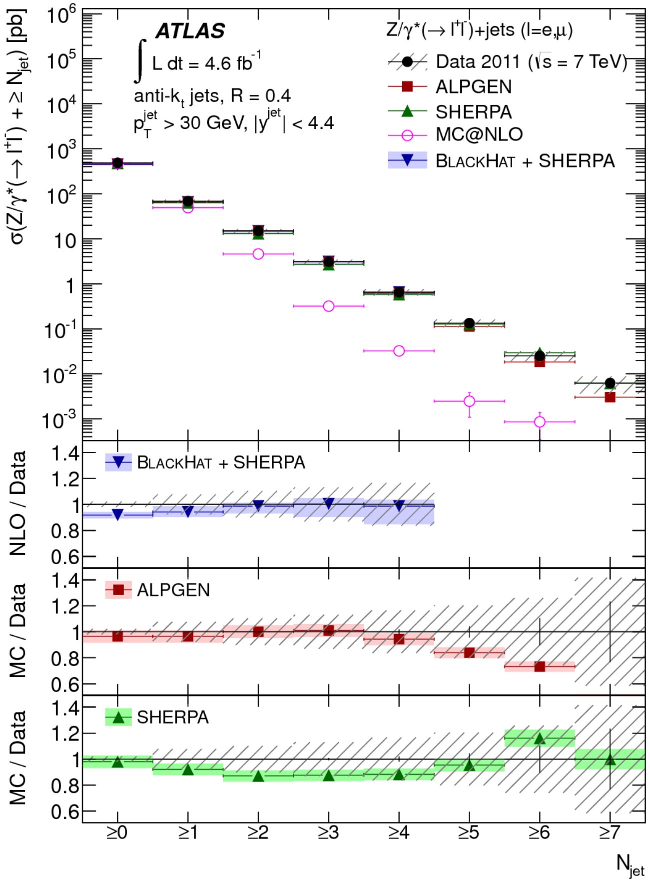


Figure 2: Overview of the ATLAS jet calibration scheme used for the 2011 dataset. The pile-up, absolute JES and the residual *in situ* corrections calibrate the scale of the jet, while the origin and the η corrections affect the direction of the jet.

ATLAS-CONF-2013-004, https://cds.cern.ch/record/1509552

- W/Z+jets measurements challenging theorists to provide accurate descriptions and experimentalists to understand detector performance even in busy environments



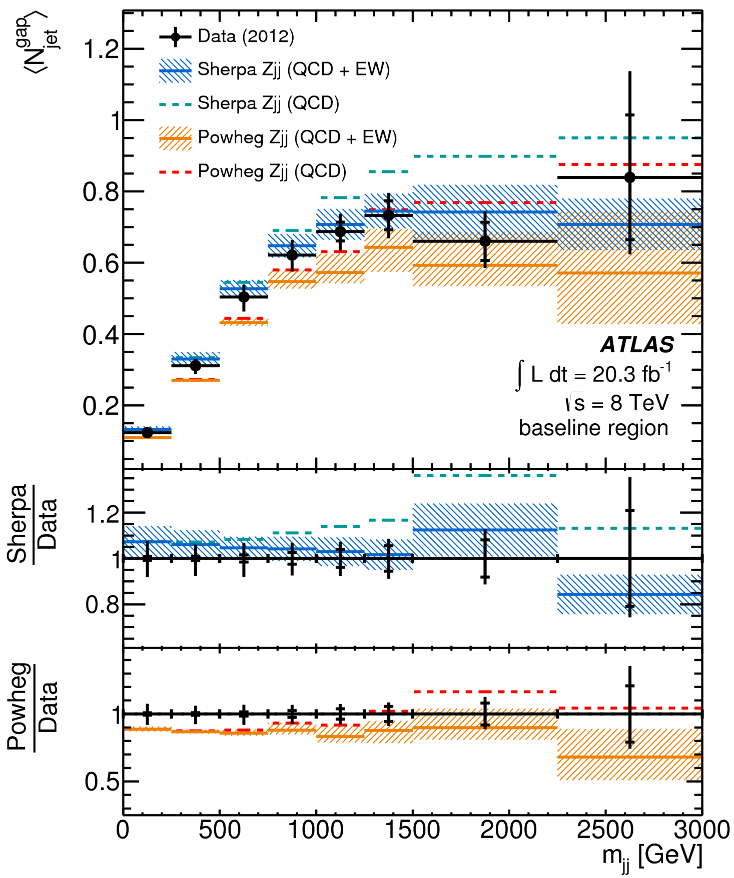


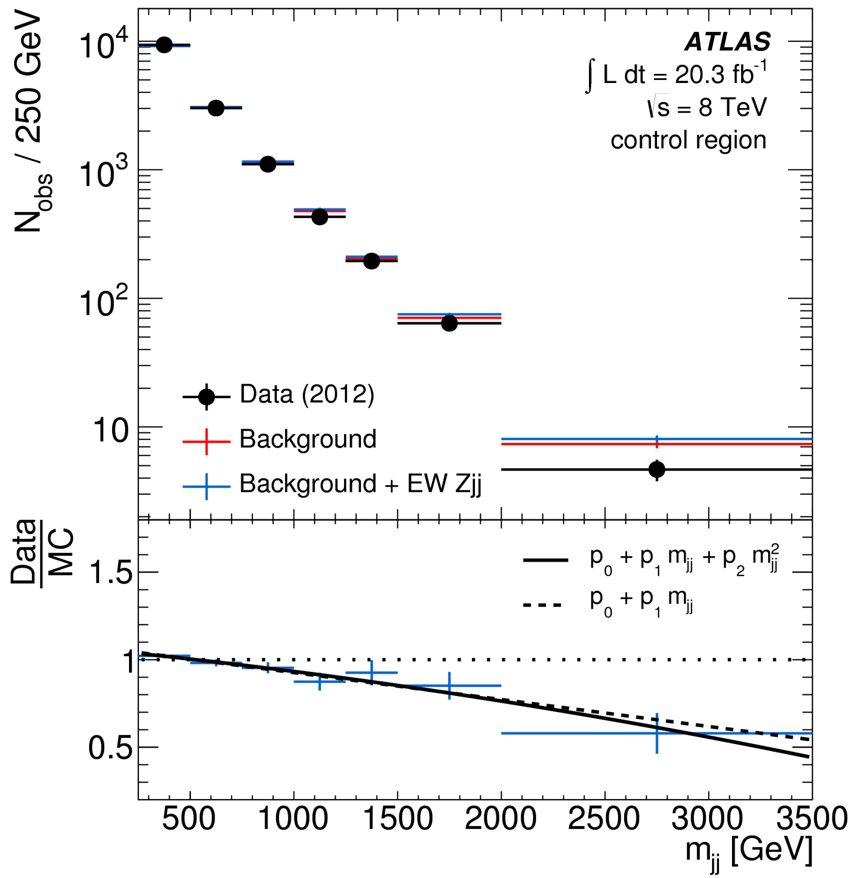
VBF Z - Event selections

Object	*baseline*	*high-mass*	*search*	*control*	*high-p_T*
Leptons	$\|\eta^\ell\| < 2.47$, $p_T^\ell > 25$ GeV				
Dilepton pair	$81 \leq m_{\ell\ell} \leq 101$ GeV				
	—		$p_T^{\ell\ell} > 20$ GeV		—
Jets	$\|y^j\| < 4.4$, $\Delta R_{j,\ell} \geq 0.3$				
	$p_T^{j1} > 55$ GeV				$p_T^{j1} > 85$ GeV
	$p_T^{j2} > 45$ GeV				$p_T^{j2} > 75$ GeV
Dijet system	—	$m_{jj} > 1$ TeV	$m_{jj} > 250$ GeV		—
Interval jets	—		$N_{\text{jet}} = 0$	$N_{\text{jet}} \geq 1$	—
Zjj system	—		$p_T^{\text{balance}} < 0.15$	$p_T^{\text{balance,3}} < 0.15$	—

VBF Z - Background control region

- Probe radiation between tag jets (strong prod.)
- Check and correct strong Z production requiring jet activity between the two tagged jets





Signal expectation

- NLO (in QCD) calculation available for electro-weak and strong $W^{\pm}W^{\pm}jj$ production
  - VBFNLO and PowhegBox → interfaced with Pythia8 for parton shower, hadronization and underlying event
- Constructive Interference of 7-12% (Sherpa, LO study)
- Main systematic from scale/PDF variations and parton shower uncertainties

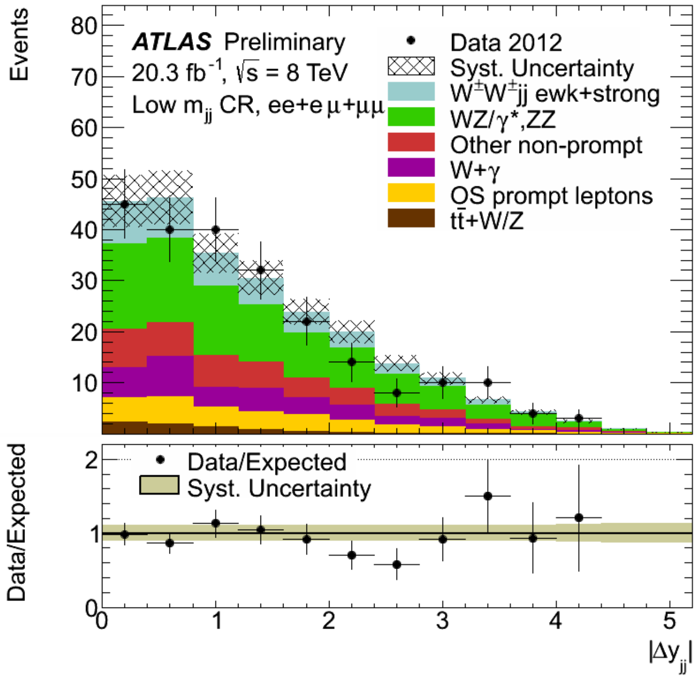
Expected cross section after selections that closely mimic experimental event selections:

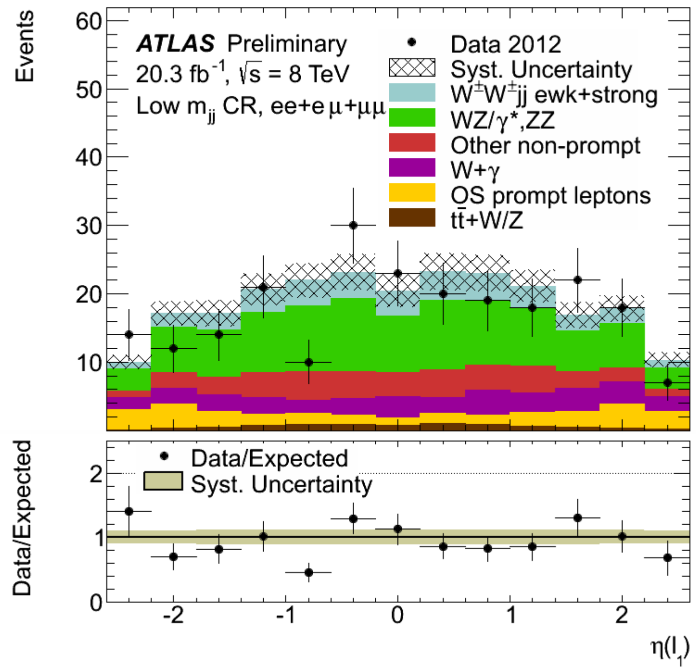
fiducial x-section [fb]	Inclusive region	VBS region
Electroweak $W^{\pm}W^{\pm}jj$	1.00 ± 0.06	0.88 ± 0.05
Strong $W^{\pm}W^{\pm}jj$	0.35 ± 0.05	0.098 ± 0.018
Interference	0.16 ± 0.08	0.07 ± 0.04
Total Signal	**1.52 ± 0.11 fb**	**0.95 ± 0.06 fb**

Summary of CR and low-mjj CR

Control Region		Tri-lepton	≤ 1 jet	b-tagged	Low m_{jj}
$e^{\pm}e^{\pm}$	exp.	36 ± 6	278 ± 28	40 ± 6	76 ± 9
	data	40	288	46	78
$e^{\pm}\mu^{\pm}$	exp.	110 ± 18	288 ± 42	75 ± 13	127 ± 16
	data	104	328	82	120
$\mu^{\pm}\mu^{\pm}$	exp.	60 ± 10	88 ± 14	25 ± 7	40 ± 6
	data	48	101	36	30

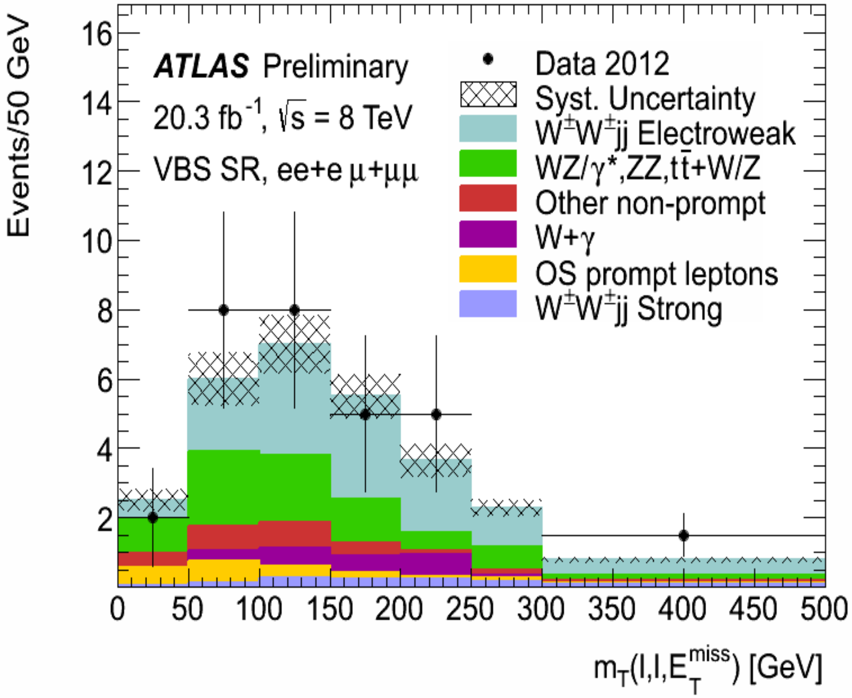
- Invert m(jj) selection to test similar admixture of backgrounds

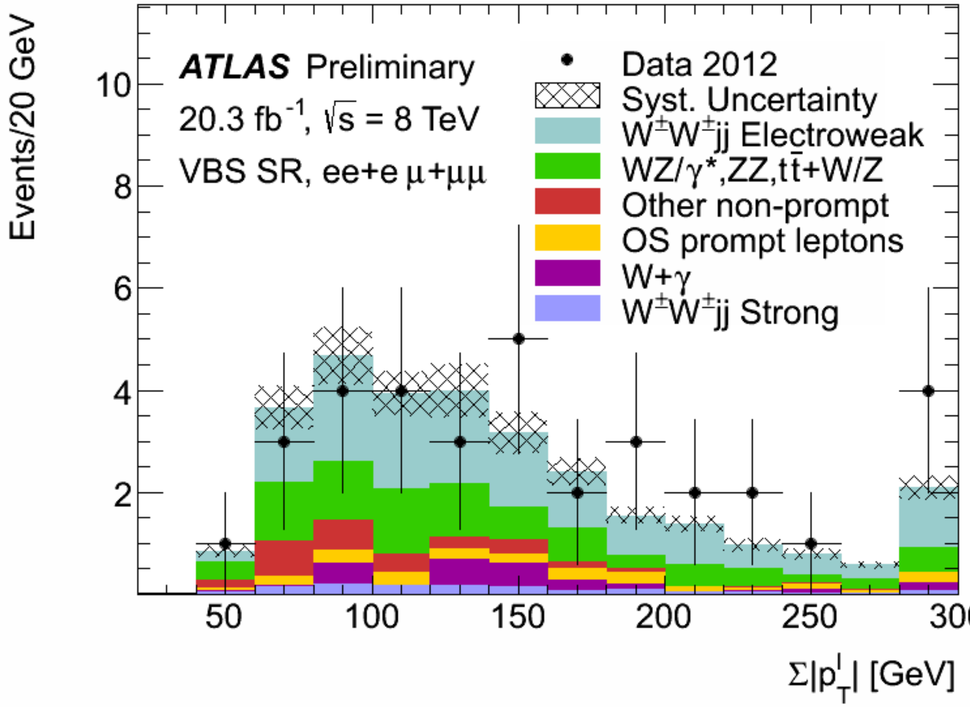




Signal region yields

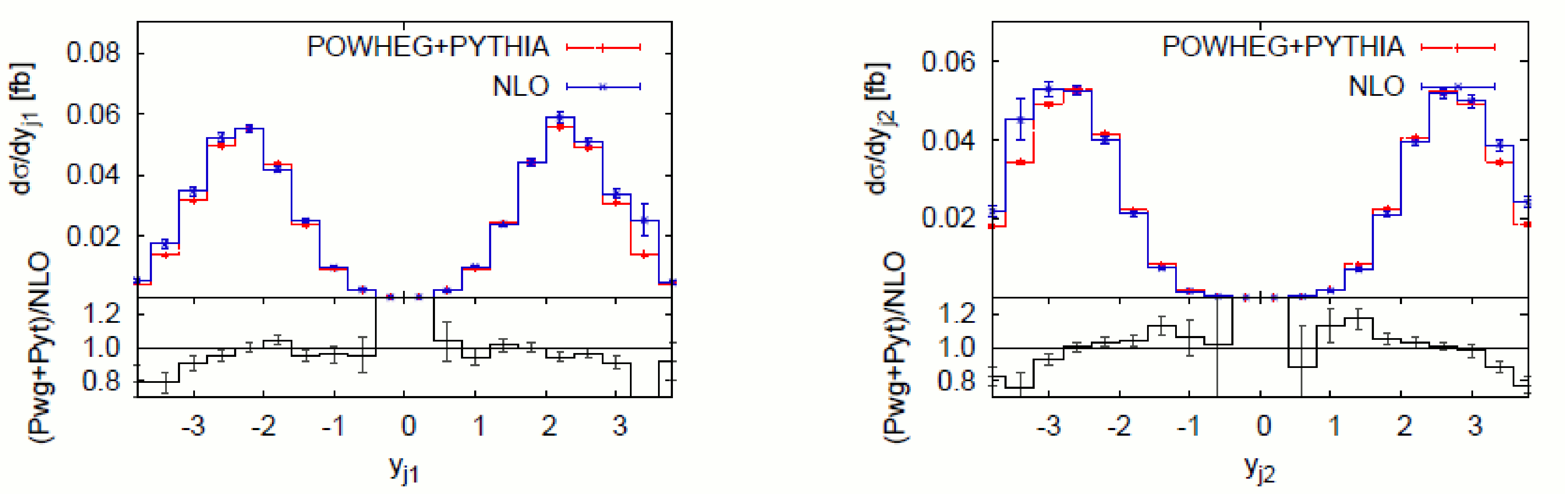
	Inclusive Region			VBS Region		
	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$
Prompt	3.0 ± 0.7	6.1 ± 1.3	2.6 ± 0.6	2.2 ± 0.5	4.2 ± 1.0	1.9 ± 0.5
Conversions	3.2 ± 0.7	2.4 ± 0.8	–	2.1 ± 0.5	1.9 ± 0.7	–
Other non-prompt	0.61 ± 0.30	1.9 ± 0.8	0.41 ± 0.22	0.50 ± 0.26	1.5 ± 0.6	0.34 ± 0.19
$W^{\pm}W^{\pm}jj$ Strong	**0.89 ± 0.15**	**2.5 ± 0.4**	**1.42 ± 0.23**	0.25 ± 0.06	0.71 ± 0.14	0.38 ± 0.08
$W^{\pm}W^{\pm}jj$ Electroweak	**3.07 ± 0.30**	**9.0 ± 0.8**	**4.9 ± 0.5**	**2.55 ± 0.25**	**7.3 ± 0.6**	**4.0 ± 0.4**
Total background	6.8 ± 1.2	10.3 ± 2.0	3.0 ± 0.6	5.0 ± 0.9	8.3 ± 1.6	2.6 ± 0.5
Total signal	**4.0 ± 0.4**	**11.4 ± 1.2**	**6.3 ± 0.7**	**2.55 ± 0.25**	**7.3 ± 0.6**	**4.0 ± 0.4**
Total predicted	10.7 ± 1.4	21.7 ± 2.6	9.3 ± 1.0	7.6 ± 1.0	15.6 ± 2.0	6.6 ± 0.8
Data	12	26	12	6	18	10





- Kinematics sensitive to electroweak component
- Candidate distributions for differential cross section measurements with more data

$W^{\pm}W^{\pm}jj$: jet η distribution



arXiv:1108.0864

Cross section likelihood

$$L(\sigma_{W^\pm W^\pm jj}, \alpha_j) = \prod_{i \in \{ee,\mu\mu,e\mu\}} \mathrm{Pois}(N_i^{\mathrm{obs}} | N_{i,\mathrm{tot}}^{\mathrm{exp}}) \prod_{j \in \mathrm{syst}} \mathrm{Gaus}(\alpha_j^0 | \alpha_j, 1)$$

$$N_{i,\mathrm{tot}}^{\mathrm{exp}}(\sigma_{W^\pm W^\pm jj}\alpha_j) = \mathcal{L} \cdot \sigma_{W^\pm W^\pm jj} \cdot A_i \cdot \varepsilon_i(\alpha_j) + \sum_b N_{i,b}(\alpha_j)$$

- α_j → nuisance parameters for systematic uncertainties
- A_i → relative acceptance for channel i (~ 1:2:1 for ee,eμ,μμ)
- ε_i → efficiency for channel i
  - 56%, 72%, 77% for ee, eμ, μμ in Inclusive region
  - 57%, 73%, 83% for ee, eμ, μμ in VBS region

Fiducial region definition

<u>Fiducial region: summary of selections</u>

Two same-charge leptons (e,μ; veto τ decays), $p_T > 25$ GeV, $|\eta| < 2.5$

- includes photons in a cone of radius ΔR=0.1 around the leptons

At least two jets $p_T > 30$ GeV, $|\eta| < 4.5$

- anti-k_T, R=0.4

$\Delta R(ll) = (\Delta\phi(ll)^2 + \Delta\eta(ll)^2)^{1/2} > 0.3$

DR(l, jet) > 0.3

m(ll) > 20 GeV

Missing Transverse Energy > 40 GeV

m(jj) > 500 GeV → <u>Inclusive fiducial region</u>

$|\Delta y(jj)| > 2.4$ → <u>VBS fiducial region</u>

anomalous Quartic Gauge Couplings

- Using electroweak $W^{\pm}W^{\pm}jj$ fiducial cross section in VBS phase space to constrain aQGC
- Effective field theory approach

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \alpha_4 (\mathrm{tr}[V_\mu V_\nu])^2 + \alpha_5 (\mathrm{tr}[V_\mu V_\mu])^2$$

  - Considering operators not already heavily constrained by tri-linear gauge coupling limits
- K-matrix unitarization schema (arXiv:0806.4145) to protect against unitarity violation
  - implemented in WHIZARD generator
- Full detector simulation shows that efficiency variations as function of $\alpha_{4,5}$ sub-dominant with respect to fiducial cross section increase

Broad resonance model

Resonance	σ	ϕ	ρ	f	t
$\Gamma[g^2M^2/(64\pi v^2)]$	6	1	$\frac{4}{3}(\frac{v^2}{M^2})$	$\frac{1}{5}$	$\frac{1}{30}$
$\Delta\alpha_4[(16\pi\Gamma/M)(v^4/M^4)]$	0	$\frac{1}{4}$	$\frac{3}{4}$	$\frac{5}{2}$	$-\frac{5}{8}$
$\Delta\alpha_5[(16\pi\Gamma/M)(v^4/M^4)]$	$\frac{1}{12}$	$-\frac{1}{12}$	$-\frac{3}{4}$	$-\frac{5}{8}$	$\frac{35}{8}$

Table 1-31. *Width Γ of the five different possible non-$SU(2)_c$ violating resonances for their decays into longitudinal EW gauge bosons, as well as their contributions to the anomalous quartic couplings parameters α_4 and α_5.*

Type of resonance	LHC 300 fb^{-1}	LHC 3000 fb^{-1}
scalar ϕ	0.9 TeV	1.3 TeV
vector ρ	1.2 TeV	1.7 TeV
tensor f	1.6 TeV	2.3 TeV

Table 1-32. *95% CL limits for the mass M of a broad resonance in simplified models obtained from limits on α_4 of Table 1-20 and using the widths of Table 1-31 with $\Gamma \sim M$.*

α_4 and α_5. In Table 1-32 we provide limits on M based on the ATLAS limits on α_4 presented in Table 1-20 (assuming $\Gamma \sim M$, $v = 0.246$ TeV). The ATLAS limits on $f_{S,0}/\Lambda^4$ (see Table 1-22) can also be translated into limits on the mass M of a broad EW resonance ($\Gamma \sim M$) as follows (using Eq. 1.61):

$$M = \left(\frac{nc_R 16\pi}{f_{S,0}/\Lambda^4}\right)^{\frac{1}{4}} \tag{1.95}$$

where c_R are the contributions to $\Delta\alpha_4$ of Table 1-31 and $n = 8, 16$ for the $WWWW$ and $ZZWW$ case,

14 TeV cross section expectations

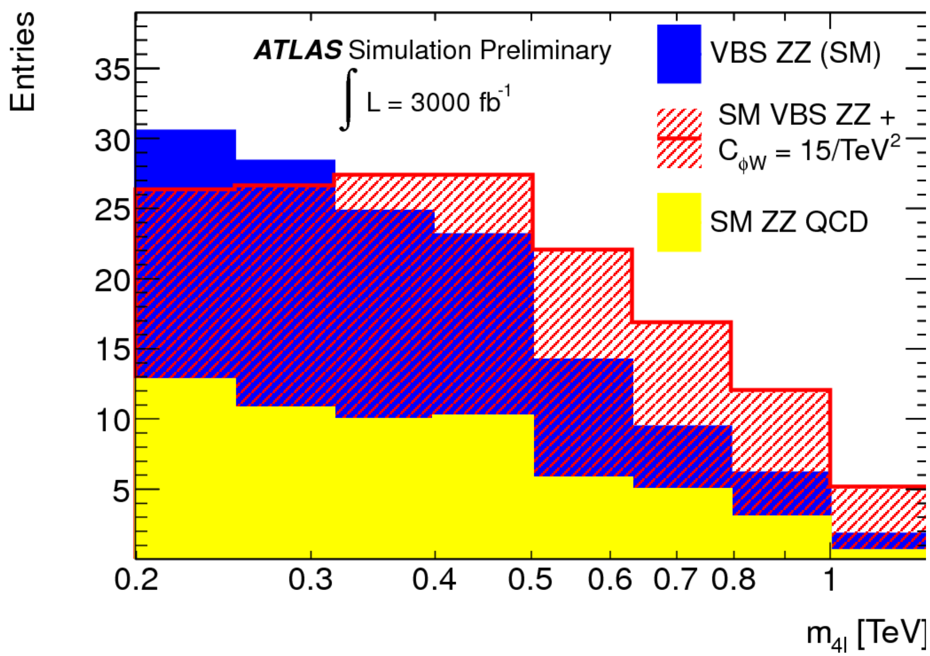
Process	σ^{fid} @ 8 TeV	σ^{fid} @ 14 TeV	Ratio 14 TeV / 8 TeV
electroweak $W^{\pm}W^{\pm}$jj	1.83 fb	7.3 fb	4
strong $W^{\pm}W^{\pm}$jj	0.74 fb	2.75 fb	4
strong $W^{\pm}Z$jj	3.11 fb	15.7 fb	5

Madgraph, LO; 2 same-charge lep p_T > 15 GeV, $|\eta|<5$; at least two jets p_T > 30 GeV, $|\eta|<5$; m(jj) > 500 GeV

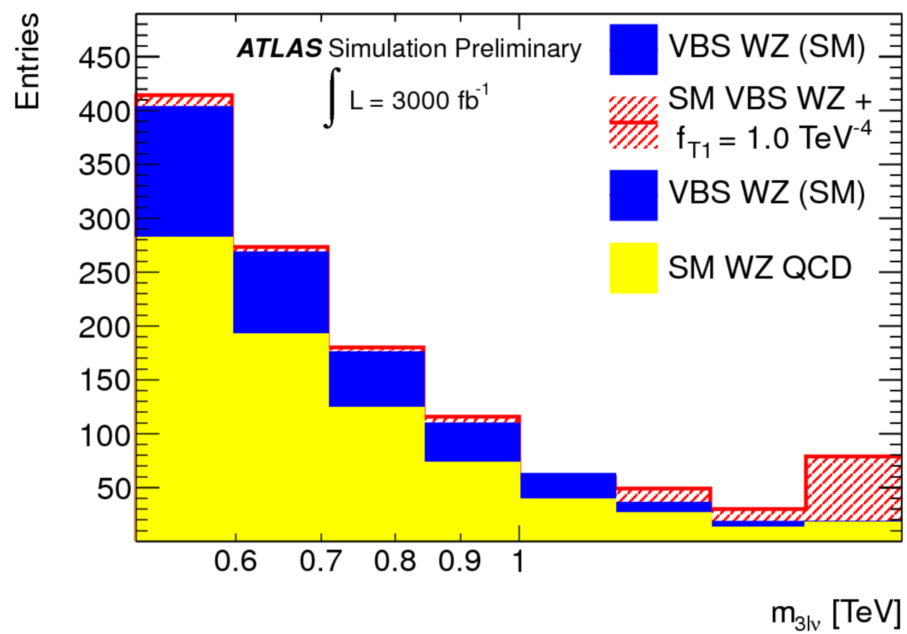
Exploring other VVjj processes

- WZjj, W^+W^-jj, ZZjj also become competitive and complementary
  - available data not enough to isolate electroweak component
  - Although already achieved evidence for explicit VBF Higgs contribution combining $W^{\pm}W^{\pm}$jj, ZZjj and $\gamma\gamma$jj channels

[Phys.Lett B 726 (2013) 88-119]



ZZjj → $l^+l^-l^+l^-$ jj



WZjj → $lll\nu$ jj

ATLAS-PHYS-PUB-2013-006

VBF Higgs results

- Latest results show 4.1σ evidence for VBF Higgs production
  - ATLAS-CONF-2014-009
  - Includes H → ττ results (VBF carries most of the sensitivity)
- Excluding H → tt, evidence for VBF Higgs production at 3.3σ
  - Phys. Lett. B 726 (2013), pp. 88-119
  - combining WW, ZZ, γγ decay channels